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## The dynamics of barchans and dome dunes Namib Desert, Namibia

Kathleen Hastings  
*University of Wollongong*

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# **The Dynamics of Barchans and Dome Dunes**

## **Namib Desert, Namibia**

Kathleen Hastings

M.Sc. (Honours)

Submitted to the Department of Geography

The University of Wollongong

April 14, 1994



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Kathleen Hastings

1994

## Abstract

Dome and barchan sand dunes are common along the west coast of the Namib Desert. In an area near Walvis Bay, central Namibia, three dome dunes and three barchans were monitored by three-dimensional topographic survey over a five-month period in order to determine dune displacement, morphologic change, and volume changes. In addition, three wind flow experiments were conducted over both dome and ~~a~~ barchan slopes to determine flow characteristics for these two slope types, and to identify the controlling factors in slipface development. Sand transport data were also collected over the experimental period to attempt to quantify erosion and deposition over the dune. These experiments and the sand transport data provided the necessary data for the development of a model of evolution of dome dunes to barchans.

Migration and volume changes were compared with regional wind data to determine correlations between the regional wind field, dune movement, and morphologic change. From this data it was determined that these dunes are not classifiable as domes or barchans by the standard criteria. As a result, two new dune types, (transitional domes and transitional barchans) were added to the existing dome and barchan classifications. Additional evidence for this classification scheme is provided by a statistical analysis of dune height, displacement and volume relationships. The results of these analyses indicate that the relationships between these variables, unlike previous studies, are not significant.

The evolutionary model is based on the erosion and deposition patterns observed over both a slipface (barchan) and a low slope (dome). Deposition and erosion are distributed fairly equally across a low slope. Over time, the dune becomes more asymmetrical in form, with increasing deposition near the crest. Flow separation becomes noticeable when the lee slope reaches an angle of between  $16^{\circ}$ - $20^{\circ}$ . With the onset of flow separation, deposition continues at a greater rate, but over a smaller area. Under a uni-directional wind, a dome will ultimately evolve into a barchan, and will assume various stages of transitional forms in the process. Under a bi-modal or variable wind regime, a dune may maintain these transitional forms

indefinitely. Other factors, such as sediment supply and exposure to sand transporting winds may also affect the evolution of a dome to barchan.

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# **Chapter 1**

## **INTRODUCTION**

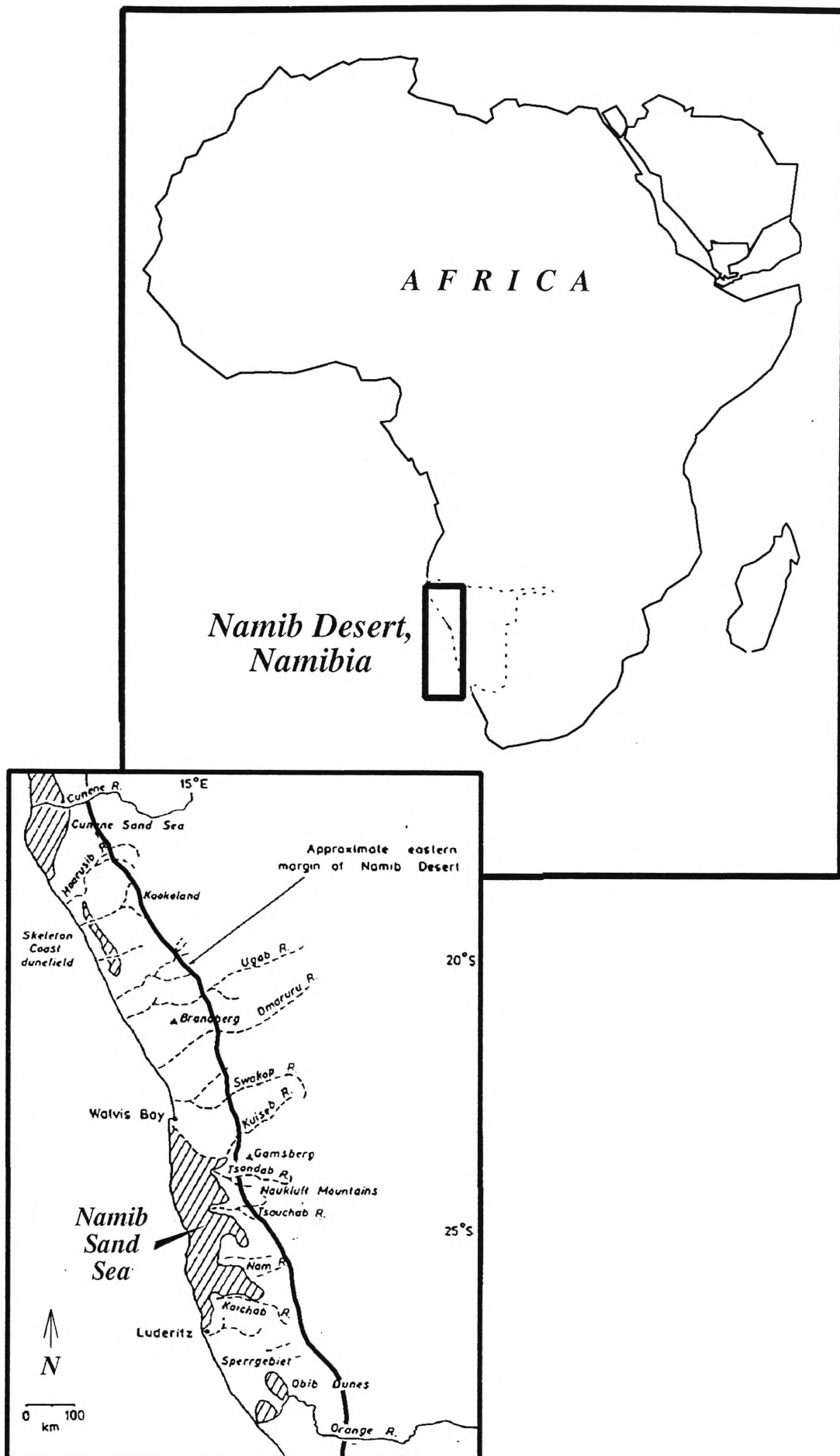
### **1.1 INTRODUCTION**

This thesis is concerned with the movement and dynamics of, and relationship between dome dunes and barchan dunes in the coastal area of the central Namib desert, Namibia. Of primary interest is the evolutionary relationship between the two dune types, as it has been observed that the dome dune often exists as a 'phase' of barchan development. As part of the study of this evolutionary process, several field experiments were conducted to examine the nature of flow, flow acceleration and flow separation over each dune type, to ascertain the nature of wind flow over the dunes and the degree of control wind flow has on the development of a slipface, and hence dune type. Sand transport (erosion/deposition) patterns were also measured in conjunction with the flow experiments.

Detailed topographic surveys were carried out to monitor medium term migration rates and morphometric change. These results were mapped and compared to previous studies of dune movement undertaken in a variety of locations around the world. The maps also provided data for computer-based quantification of dune volume. In addition, wind data obtained from weather stations near the study area were used to correlate dune migration and morphologic change with wind velocity and direction.

### **1.2 REGIONAL GEOLOGICAL & GEOGRAPHICAL SETTING**

The Namib Desert lies along the western coast of southern Africa, extending 2000 km north from the Olifants River in South Africa, to the Carunjamba River in southern Angola (Fig. 1.1). Within this desert lies the Namib Sand Sea, comprising an area of approximately 34,000



(from Lancaster, 1989)

**Figure 1.1** Location map showing the Namib Sand Sea and the Namib Desert

sq. km. (Barnard, 1973; Lancaster, 1989). It extends north from Luderitz to just south of Walvis Bay where the main northern boundary is sharply defined by the Kuiseb River. A small area of dunes extends to the north of the main sand sea, from the Kuiseb delta north to the Swakopmund River.

The Namib Sand Sea is believed to be of Pleistocene to Recent age, although it may have had its origins in the more arid Pliocene (Ward et al., 1983). The sands are derived from the Orange River, as well as from the reworking of the Tsondab Sandstone Formation, an early to Middle Tertiary deposit comprising red-brown fossil dunes and sand sheets.

The eastern edge of the sand sea is bounded by the Great Escarpment, which rises to 2500m at its highest point. It is an Early Cretaceous erosional feature cut into the Damara Sequence mica schists (Precambrian) to the north and the Namaqua Province granites and gneisses to the south (Selby, 1977; Lancaster, 1989).

### 1.3 CLIMATE

The climate of the Namib is arid to hyper-arid, with relatively cool temperatures, particularly in coastal areas. Temperatures and climatic characteristics vary considerably from the cool coastal zone to the hot, dry interior. Mean annual daily temperatures range from 17°C at the coast to 33°C inland. Maximum temperatures of 40°C occur inland during late summer, with minimum temperatures ranging from 15°C to 18°C during mid to late summer. Winter minimum temperatures range from 4°C to 8°C, resulting in an average regional minimum temperature range of 13°C to 16°C (Lancaster, 1989).

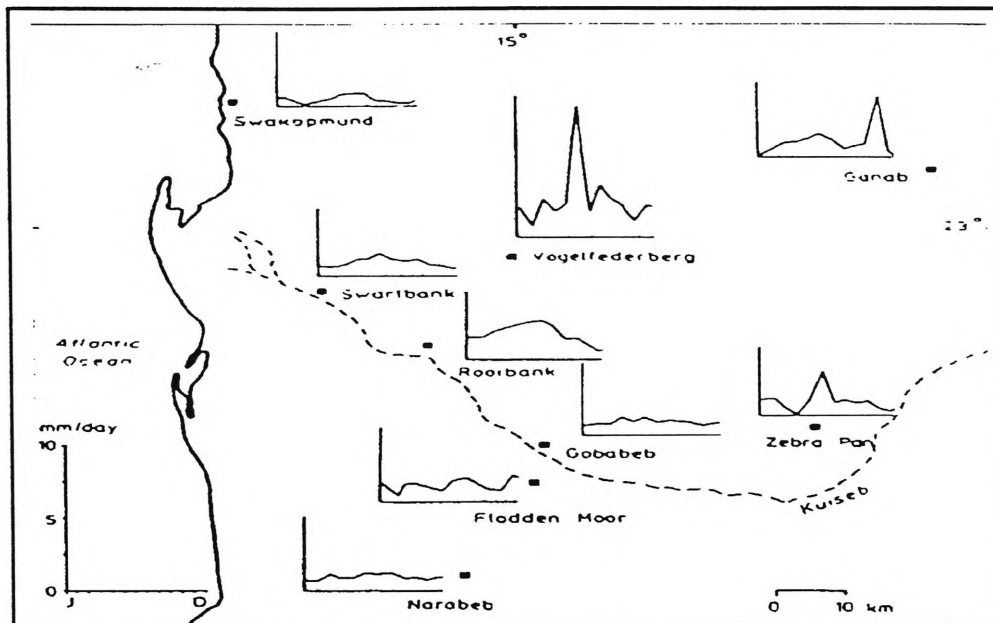
The climate and circulation patterns of the central and southern Namib are strongly influenced by the South Atlantic anticyclone located offshore at approximately 30°S. The presence of this

anticyclonic cell explains the aridity of the region. Moist air masses can reach the dry interior only when this cell is weak, and then have only minimal impact on the drier regions. Consequently, throughout the year southerly winds outblowing around the South Atlantic high are diverted inland as a SSW-SW sea breeze by the thermal contrast between the desert and the cold upwelling ocean waters of the Benguela Current (Lancaster, 1985). These winds are seasonally variable and reach maximum frequency and intensity during the early to mid summer months (September to January) when the anticyclone is at its strongest and the thermal contrast between the inland and coastal areas is greatest (Lancaster, 1984).

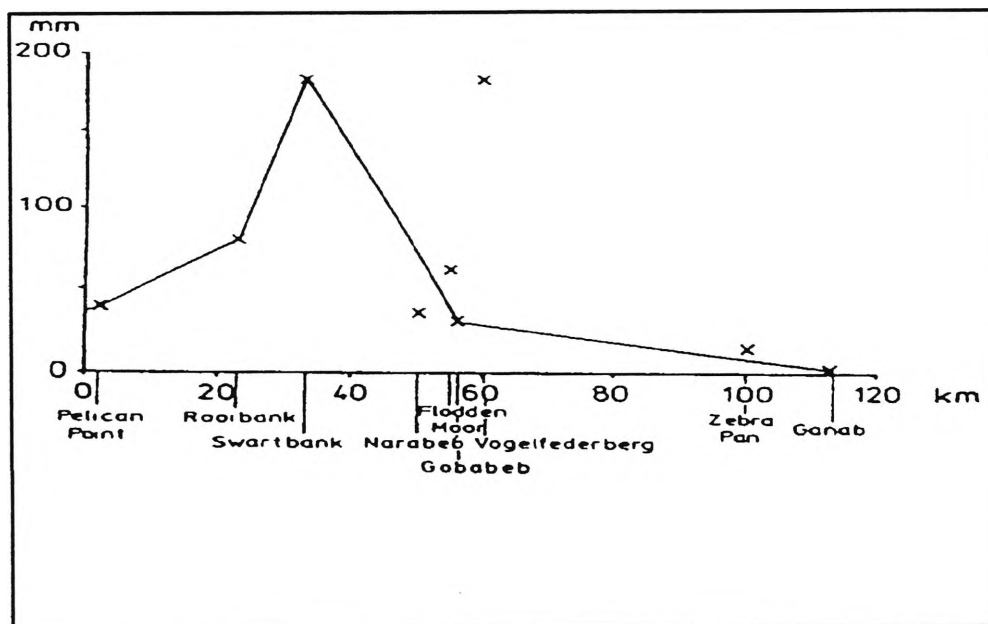
Moist oceanic air flowing over the Benguela Current commonly results in fog. Fog occurs more regularly than rain and reaches 100 km inland (Lancaster et al., 1984). The number of days of fog vary dramatically from the coast inland (Fig. 1.2). Up to 65 fog days per year occur in coastal areas, decreasing to 15 or less along the eastern edge of the desert (Lancaster, 1989). Fogs are most common along the coast in winter but inland they occur more frequently during the spring and early summer months. Although more fog days occur along the coast, the actual amount of fog precipitation increases with distance inland. Fog precipitation averages 34 mm per year along the coast, increasing to a maximum of 184 mm at 35 - 60 km inland, and decreasing to 15 mm at the eastern margins of the desert. Rainfall, by comparison, increases from 15 mm at the coast to 87 mm near the eastern edge of the escarpment (Lancaster et al., 1984).

### 1.3.1 Wind Regime

Wind flow patterns in the Namib exhibit both seasonal and daily variations (Fig. 1.3). Winds tend to be north or west during summer (December to February), east to northeast from autumn to late winter (March to August), and south to southwest in spring (September to November) (Lancaster et al., 1984).



Mean amount of fog-water precipitation calculated per fog day.



Mean annual fog-water precipitation in the central Namib plotted against distance from the coast. Values for longer term stations are connected while shorter-term stations are indicated by (x) only (from Lancaster et al., 1984).

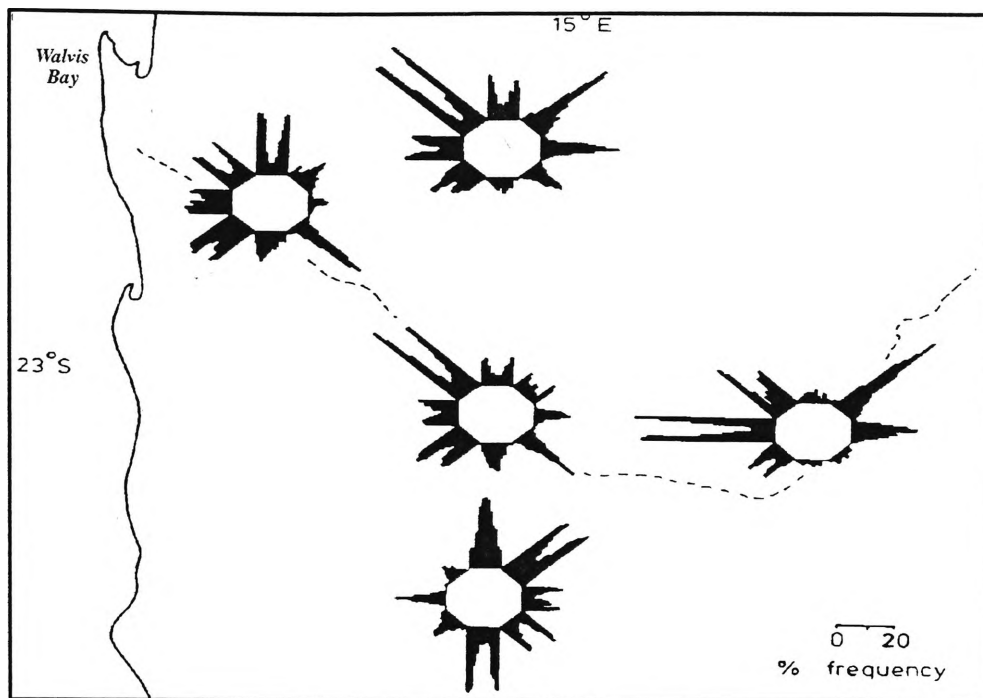
Figure 1.2 Precipitating fog in the Central Namib.

### 1.3.2 Daily Wind Cycles

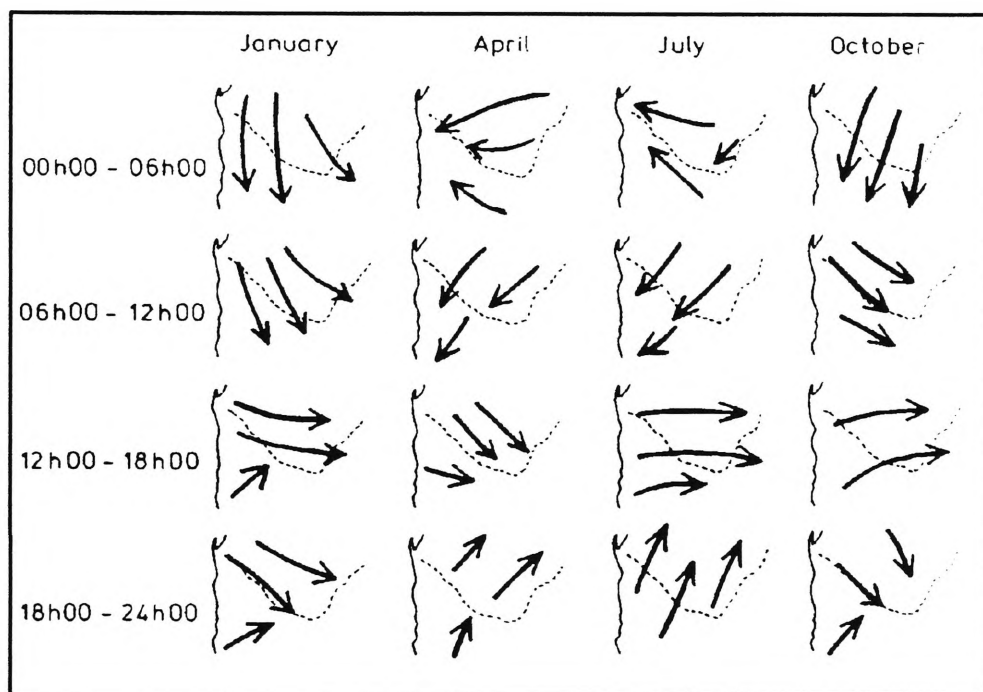
Tyson and Seely (1980) have studied the fluctuations of wind patterns over the central Namib, where widespread thermo-topographic winds result in pronounced diurnal and seasonal oscillations. During all seasons, there is a regular daily cycle of wind direction and velocity. Summer mornings are characterized by light northerly winds, lasting until midday or late afternoon, when winds strengthen from the SW or SSW, reaching peak velocity during the late afternoon. In winter, the pattern is similar but sea breezes tend to be weaker. Winter morning winds are light to moderate east to NE. Later, winds may cease or become light northerlies until the SW sea breeze occurs late in the afternoon. The occasional 'berg' wind originates from the southeast or ESE in the early morning and becomes northeast to ENE and increases in velocity, peaking during the late morning. Afternoons are generally calm with these strong easterly winds, with light southwesterly sea breezes occurring during mid- to late afternoon (Lancaster, 1989).

### 1.3.3 Seasonal Wind Characteristics

Lancaster et al. (1984) have observed that winds from the west and southwest represented 16 - 40% of all winds recorded, with 30 - 40% of these winds occurring during the early summer months, and 7 - 30% occurring during winter (July). Northwest to NNE winds with annual frequencies of 14 - 34% occur during the summer months, primarily during the morning. During the winter, winds from east and northeast predominate, comprising 40 - 60% of all winds recorded from the period April to August. High velocity easterly or 'berg' winds occur during autumn and winter months, reaching velocities of up to 60 km/hour. At Walvis Bay on 21 July 1989, maximum wind speeds of 65 km/hour (18m/sec) were recorded for one berg wind event (Namib Times, 21 July 1989).



**Seasonal variation of wind directions in the central Namib Desert. Wind stars show proportion of winds from major compass directions in each month, clockwise from January to December (from Lancaster, 1989).**



**Daily cycle of wind direction in the central Namib Desert (from Lancaster, 1989).**

**Figure 1.3 Wind regime in the Namib Desert**

## 1.4 DUNES OF THE NAMIB

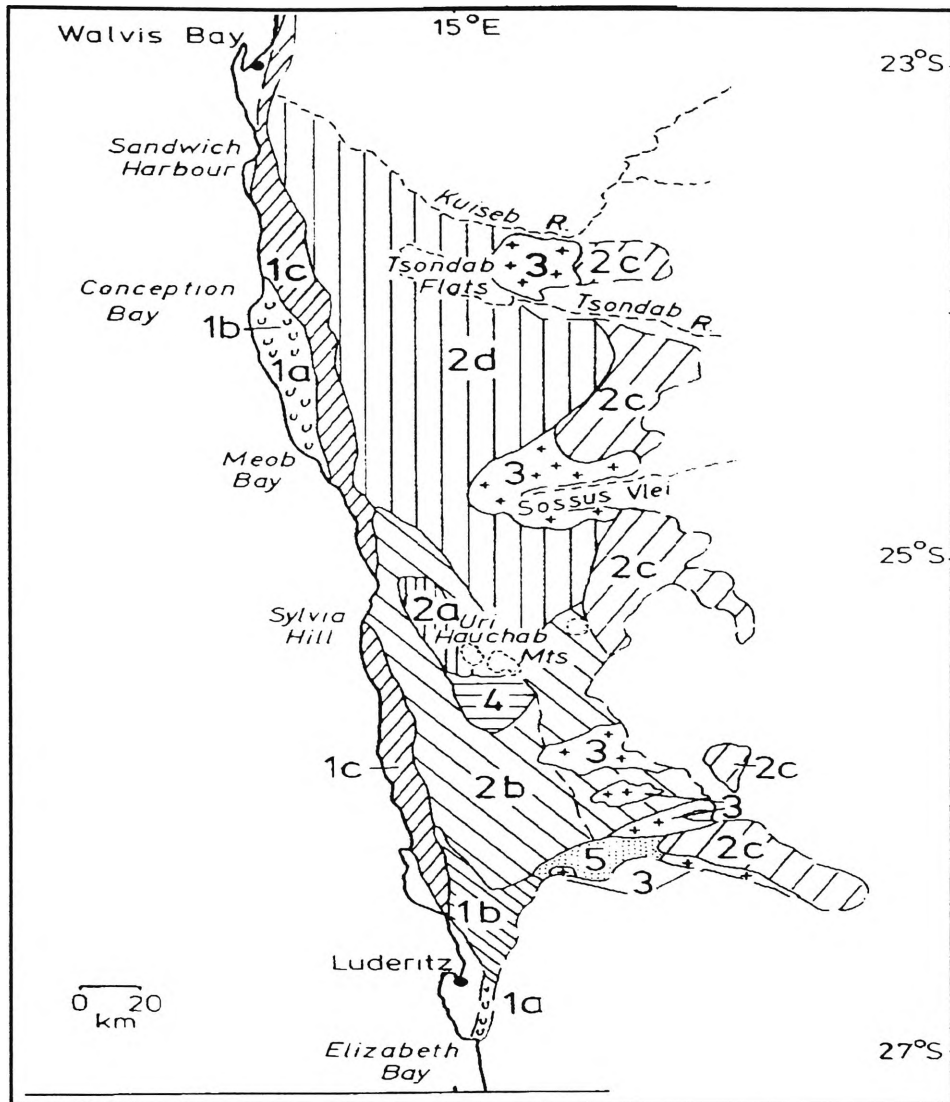
Sand cover throughout the sand sea is fairly continuous, and is interspersed with extensive interdune gravel plains. Sand cover exists in the form of dunes, their type and spatial variability determined primarily by sediment supply and climate, especially wind flow. Barnard (1973) recognized three geomorphological provinces within the Namib desert: the linear dunes of the central area, the multi-faceted dunes of the eastern area, and the coastal strip containing mainly transverse dunes (Fig. 1.4.). The following section briefly describes some of the characteristics of the main dune types present in the Namib Sand Sea. Most of the following information was obtained from J. D. Ward's compilation of characteristics of the major dune types of the Namib Desert (Dunes '89 Excursion Handbook) except where otherwise noted.

### 1.4.1 Linear Dunes

The linear, or seif, dune type predominates within the Namib, occurring within the central area, trending primarily north - south but also ranging from northwest to southeast. Most of these compound and complex linear dunes are formed under bimodal wind regimes which blow at an obtuse angle to the dunes, and generate low to moderate potential sand flow (Lancaster, 1989). These dunes may be up to 60 km long and from 50 to 170 m in height and are spaced between 1000 to 2500 m apart. Net direction of sand movement is northerly, with the northern boundary ending abruptly at the Lower Kuiseb River, where periodic flooding prevents continued northerly migration.



### Distribution of different dunes types in the Namib Sand Sea:



- 1 = Crescentic dunes
  - a = barchans
  - b = simple crescentic dunes
  - c = compound crescentic dunes
- 2 = Linear dunes
  - a = simple
  - b = compound, straight
  - c = compound, anastomosing
  - d = complex
- 3 = Star dunes and chains of star dunes
- 4 = Large zibar
- 5 = Sand sheets

(from Lancaster, 1989)

**Figure 1.4 Dune types of the Namib Sand Sea**

#### 1.4.2 Star Dunes

Star, or stellate dunes occur in the eastern area of the Namib. They form under multidirectional, or complex wind regimes and are recognized by their high central peak with radially extending multiple slipfaces (McKee, 1979), providing the characteristic 'star' shape. The Namib dunes may be up to 300m in height and from 600m to 2600m apart. In the northern part of the Namib dunes classified as star dunes tend to demonstrate a preferred crestal alignment, usually parallel to the nearby linear dunes, while the dunes of the southern Namib represent a more classic star shape due to distinctly tri-modal winds (Lancaster, 1989).

Sand transport on star dunes is minimal due to the opposing directions of sand transporting winds. Dune growth tends to occur as a result of erosion and redeposition of sand on opposite sides of the slipface, resulting in upward growth by deposition rather than extension (Lancaster, 1989).

#### 1.4.3 Transverse and Barchanoidal Dunes

The coastal area of the Namib, from its southern to northern boundaries, is dominated by simple and compound transverse and barchanoidal (crescentic) dunes forming under the high velocity, uni-modal wind regime common along Namibian coastal areas. These dunes range in height from 3 to 50m, with heights in the lower range being more common. Near Walvis Bay and Sandwich Harbour, transverse dune heights have been measured up to 100m.

Net direction of movement is from NNW to ENE, with local reversals to SSW-W caused by easterly winds in winter. Migration rates vary, with dunes in the southern Namib migrating at average rates of 24-60m/year, while transverse dunes of the central Namib migrate from 1-

15m/year. These differences are probably attributable to local variation in wind velocity as well as overall dune size, with smaller dunes migrating more rapidly than larger ones.

#### 1.4.4 Barchan and Dome Dunes

Barchan and dome dunes also occur in the Namib coastal area, alongside the complex transverse and barchanoidal ridges outlined above. These three general dune types often represent a specific stage in an evolutionary process. Commonly, a barchan dune will evolve from a dome-like form, to a fully crescentic shape, to a complex barchanoidal ridge, to a transverse dune or ridge. This process may reverse and/or continue, depending on wind direction and sand supply.

### 1.5 THE STUDY AREA

Two areas were selected for this study. Both lie within the small northern extension of the Namib Sand Sea, which continues approximately 40 km beyond the Kuiseb River delta north to the Swakopmund River (Fig. 1.5).

#### 1.5.1 Study Area 1 (Walvis Bay)

Immediately south and east of Walvis Bay lies a small barchan dune field adjacent to the Kuiseb River delta and sited on an extensive, terraced gravel plain (Fig. 1.6). This area represents a northern extension of the main Namib Sand Sea and contains both discrete barchan dunes with well-developed slipfaces and crescentic forms interspersed with barchanoidal ridges and dome dunes. These dunes are often spaced many metres apart, resulting in limited dune-to-dune sand supply, and no immediately significant sand source. Heights vary from less than one metre up to approximately ten meters. Towards the northeastern margin, the dunes lose

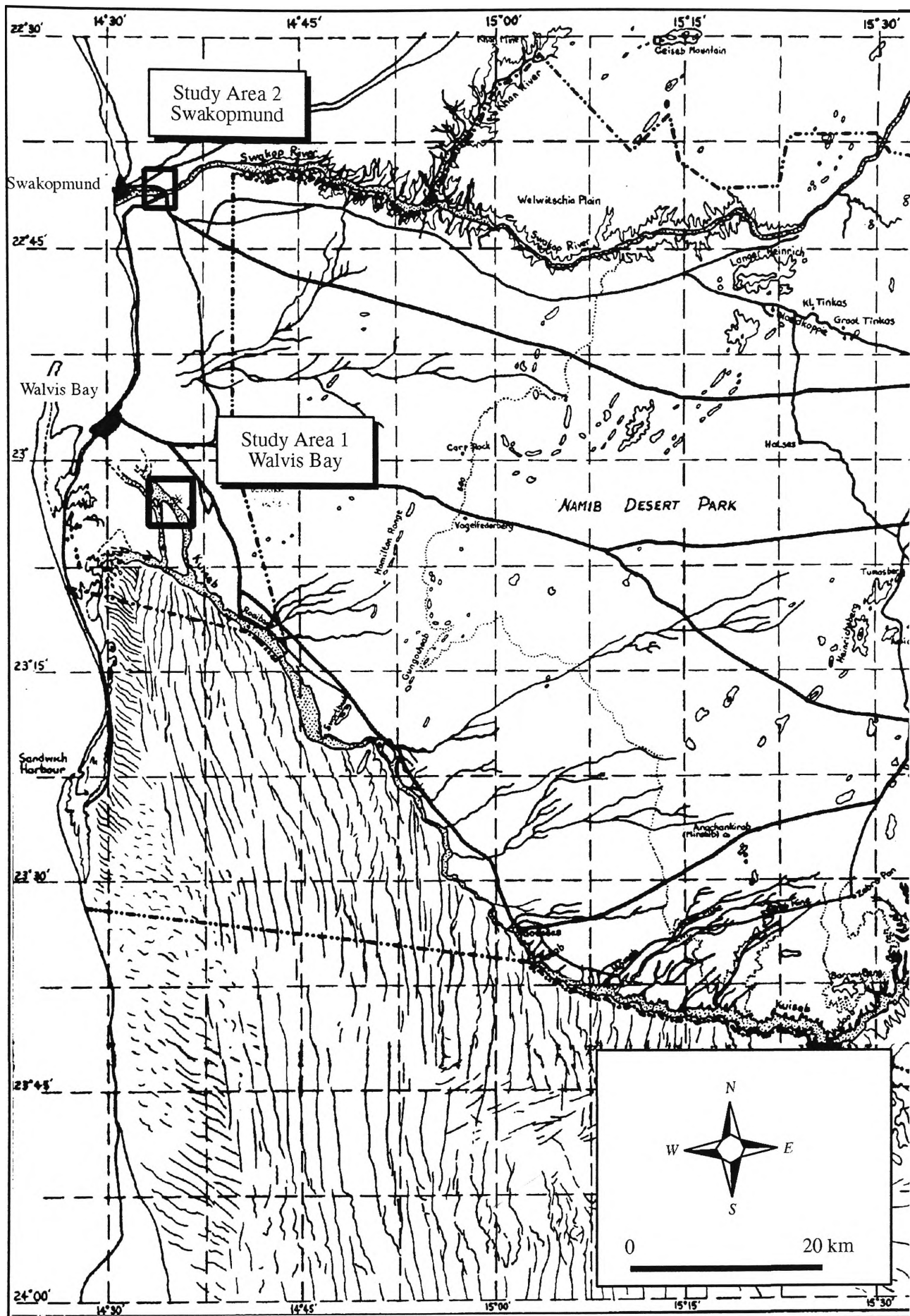
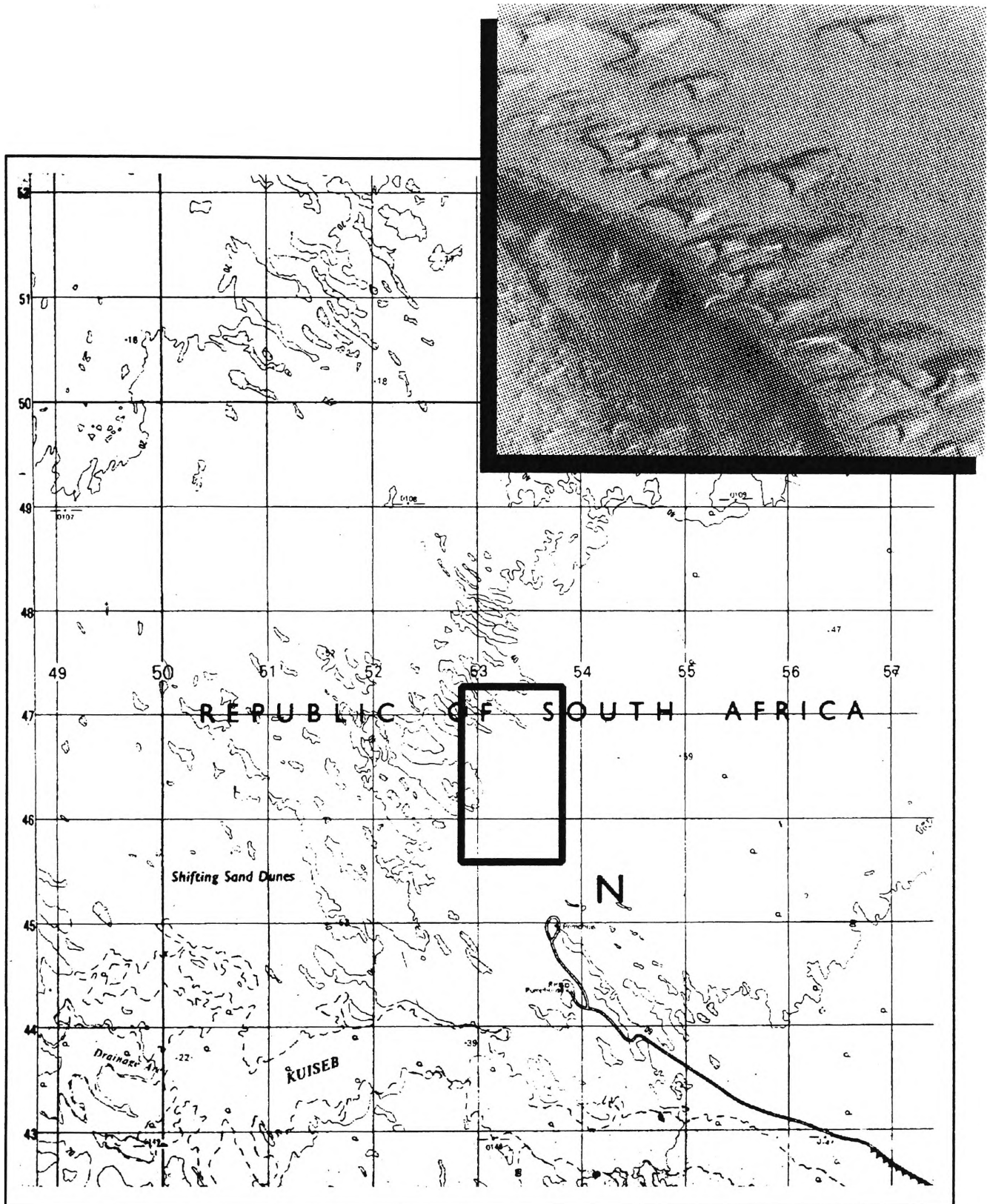


Figure 1.5 Study areas

Aerial view of the Walvis Bay dunefield, showing barchan and barchanoidal dune types adjacent to the Kuiseb River delta.



Approximate location of the Walvis Bay study area, delineated by the black rectangle.

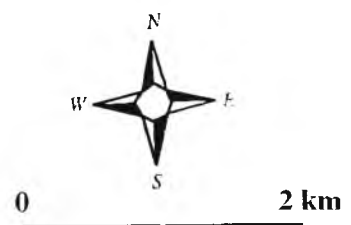


Figure 1.6 Walvis Bay study area

their distinct barchan shape, gradually evolving into more complex transverse dune forms, with heights decreasing to less than 0.5 metres for most dunes. Slipface development on the majority of these dunes is common, despite their relatively low height and irregular form.

### 1.5.2 Study Area 2 (Swakopmund)

Continuing north of this dune field, towards Swakopmund, these transverse and barchanoid dune chains continue to dominate the coastal area, with dune heights generally increasing. Near Swakopmund, adjacent to the Swakopmund River lies another dune field comprised of complex transverse dunes, with heights ranging from approximately 2-20m (Fig. 1.7). Several small barchan and dome dunes with heights up to two meters lie within the interdune areas on the downwind margin.

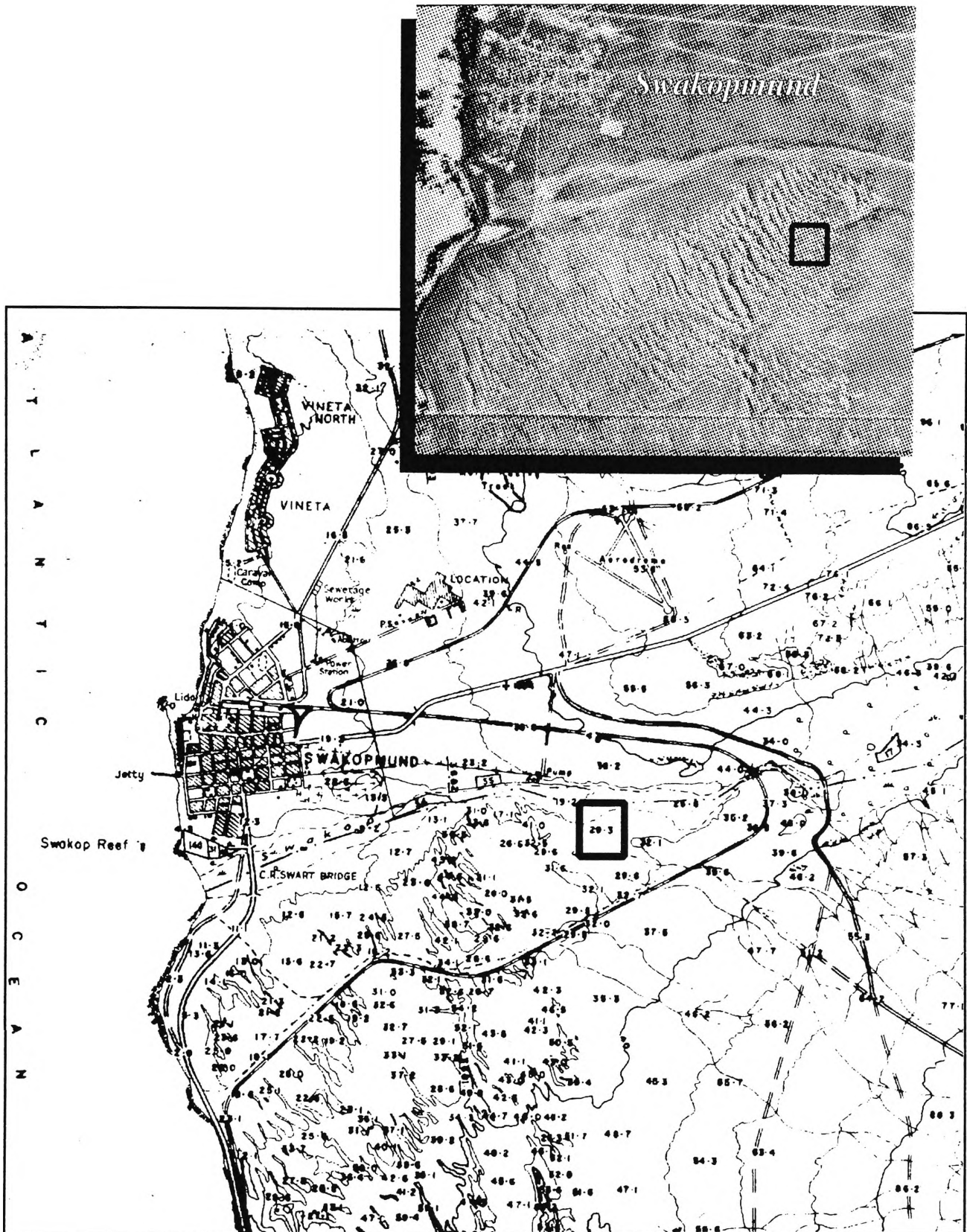
## 1.6 WIND AND SAND TRANSPORT

Lancaster (1985) has studied wind flow characteristics and sand transport in the region using data from wind recorders located at weather stations throughout the Namib Desert. At all stations, winds blow above the threshold velocity for sand movement (4.4 m/s) 20% of the time. A definite seasonal pattern of wind flow and direction exists in the region. Sand movement occurs 30 to 40% of the time during September to January. In April and May sand transport occurs 15 - 20% of the time. The influence of easterly 'berg' winds is characterized by a secondary peak in sand transport, particularly noticeable at the most northerly stations.

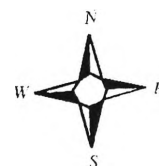
Lancaster recognizes two main sand transport sectors: SSE-SW and E-NE, with a third sector (N-NNW) being locally important (Fig. 1.8). Between 80 - 90% of sand transport near the coast occurs from the SSE -SSW sector, decreasing to a minimum of 10 -25% at inland stations. The E-NE sector is of lesser importance along the coast, accounting for less than



Aerial view of the Swakopmund dunefield, showing transverse, dome, and barchan dunes.



Approximate location of the Swakopmund study area, delineated by black rectangle.



0 2 km

Figure 1.7 Swakopmund study area

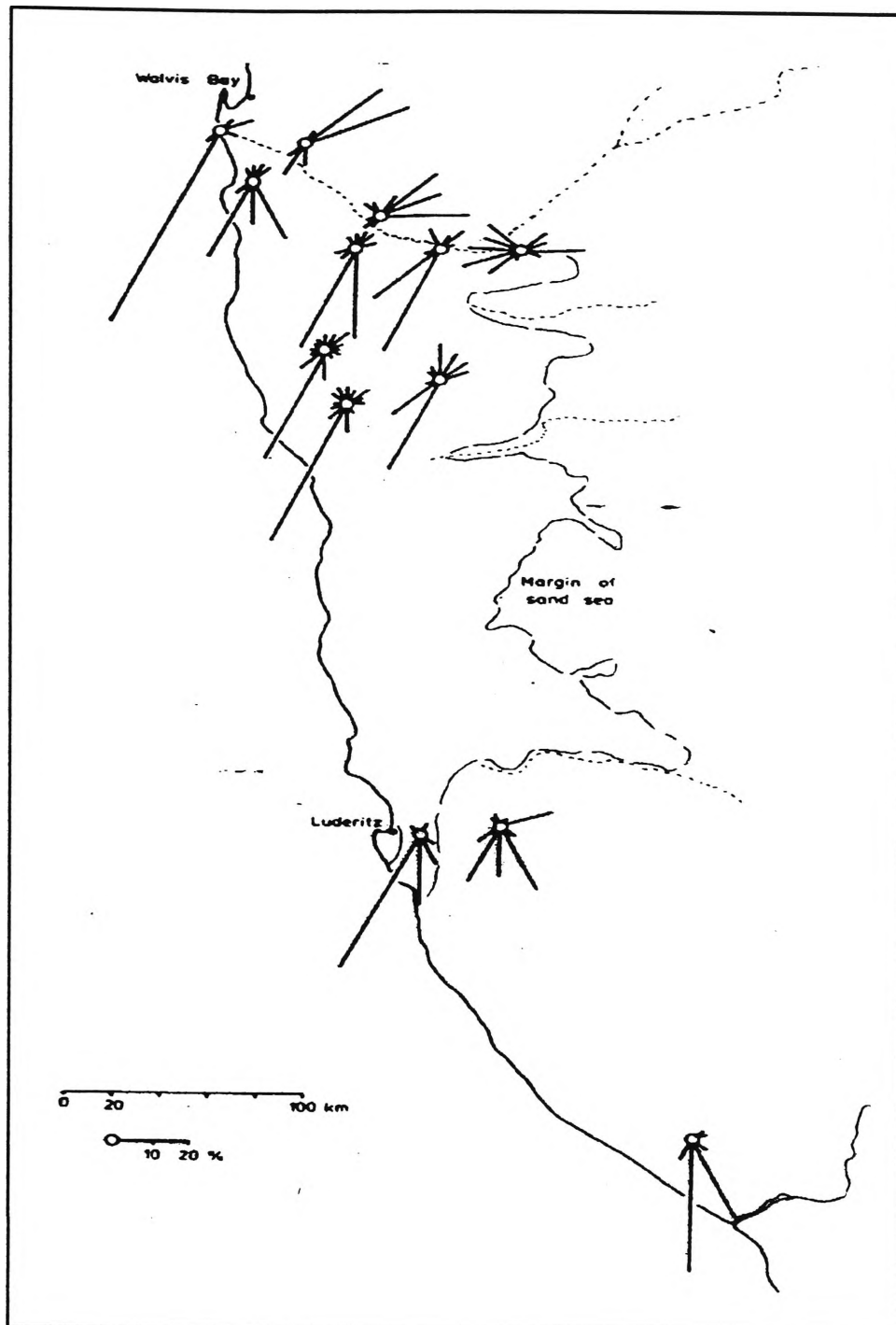
10% of annual sand flow. This indicates the infrequent penetration of the 'berg' winds, although in coastal areas easterly winds can account for 30-40% of sand flow during July and August. Maximum total potential sand flow at coastal stations occurs in November - February.

Seasonal variability of sand transport along the coast is minimal, compared to inland areas. Here, during the period September to April, sand flow from S-SW predominates and may account for 90% of sand transport during the summer months (December and January). In winter, sand flow from this sector may be as low as 10%. In the inland areas, maximum total potential sand flow occurs in December and January.

At almost all stations the annual resultant direction of sand flow is towards the N-NE or NNW. Seasonal fluctuations result in summer sand flow at all stations becoming N-NE, with both total and resultant sand flow peaking during this time. Winter is characterized by low resultant sand flow, directed towards the SW or west, though at northern stations maximum resultant sand flow occurs during June or July.

The relationship of total and resultant sand flow is explained by the ratio  $RDP/DP$ , where  $DP$  represents the drift potential (expressed as vector units) derived from the modified Lettau (1975) equation for sand drift, and  $RDP$  is the resultant drift potential. Values derived from this formula indicate the sand-transporting capacity of the wind for the time period of the wind summary. The index of the directional variability of the wind is the ratio of the resultant drift potential to the drift potential ( $RDP/DP$ ) (Fryberger and Dean, 1979). Drift potential is discussed in detail in Chapter Six. The unidirectional index ( $UDI$ ) (Wilson, 1971) further defines the relationship between total and resultant sand transport. The  $UDI$  is a ratio of wind velocity to directional variability. For example, an area with very strong winds with little directional fluctuation will have a comparatively high  $UDI$ , while lower velocity winds originating from a number of directions will have a lower  $UDI$ .





Annual pattern of potential sand flow in the central and southern Namib  
(from Lancaster, 1985).

**Figure 1.8 Annual potential sand flow in the Namib Desert**

Three sand flow regimes in the Namib are recognized on the basis of their annual UDI: coastal stations with a UDI of 0.7, stations up to 60 kilometres inland with a UDI of 0.4-0.6, and stations along the eastern margin with a UDI of 0.2-0.3. High energy wind regimes with low direction variability (high UDI) predominate along the coastal areas, while areas of low UDI, i.e. low wind energy and increased directional variability, occur inland. Given that annual resultant sand flow is towards the NE, it is apparent that sand is being transported from areas of high wind energy and low directional variability to areas where wind energy is less and directional variability greater, implying that the rate and direction of sand transport into an area is greater than out of it.

This pattern of sand flow has been utilised in building a model for sand accumulation in the Namib Sand Sea. According to Lancaster (1983), the spatial distribution of various sand dune types in the Namib indicate the existence of a relationship between resultant sand transport and dune type. Large complex linear and star dunes of the central and northern areas of the sand sea are larger than the linear dunes in southern areas, indicating a greater volume and net accumulation of sand. Further evidence indicates a relationship between wind, sand movement and dune type. In areas of high UDI, barchans and transverse dunes occur. Linear dunes occur in the central Namib, where wind energy and transport rates are low and UDI is moderate. The large star dunes occur in areas with the lowest UDI.

## 1.7 RESEARCH OUTLINE

The general aim of this thesis is to observe, monitor and measure the changes in barchan and dome dune forms at two coastal sites, and to attempt an analysis and quantification of the evolutionary relationship between the two dune types.

Five specific thesis aims are recognized:

- (1) to determine the nature of and inter-relationship between wind velocity and flow direction and rates and direction of dune movement.
- (2) to quantify volumetric changes of each dune and examine the relationship between these changes and wind flow and migration rates.
- (3) to observe and record both short and long term morphologic change, and through experimentation and topographic mapping, to examine relationships between dune shape and flow behaviour.
- (4) to identify and compare erosional and depositional patterns across a barchan type dune with a well-developed slipface and a dome type dune with no slipface development.
- (5) to attempt a formulation of a preliminary predictive model for dome and barchan dune inter-relationships, dynamics and development.

Three representative dunes were chosen from the Walvis Bay/Swakopmund dune fields for the purposes of this project. Each dune exhibited either a fully barchanoidal or dome-like form during the initial stages of the study. The morphological evolution of the dunes was monitored over the 5 -month study period using a series of regular topographic surveys. In conjunction with these surveys, wind flow experiments were conducted and sand transport and deposition were monitored in both locations and under a variety of wind conditions to determine relationships between the dune forms and flow conditions. A wind tunnel was employed in an attempt to further correlate and quantify sand movement, wind flow velocity and morphologic change.

### 1.7.1 Thesis organization

This thesis contains eight chapters and two Appendices. Chapter Two presents a detailed review of research relevant to this study. Chapter Three details the methodology employed in data collection and analysis. Chapter Four presents results of dune displacement and volume calculations, and some brief observations on the relationships between dune morphology, displacement, and volume, and how these results compare to previous studies. Chapter Five discusses the morphometric characteristics of both Walvis Bay and Swakopmund dunes, and also provides additional observations of height, volume, and displacement relationships. Chapter Six contains a detailed regional wind analysis and resulting sand transport. The influence of wind variations on dune morphology, displacement, and volume is further examined. Chapter Seven contains the methodology and results of a series of flow experiments conducted in the Swakopmund area. Chapter Eight presents the final conclusions. Appendix One contains 41 contour maps representing the results of six topographic surveys of seven dunes. (SW3 was surveyed only six times). Appendix Two contains an example of a worked equation used for calculating resultants.

## Chapter 2

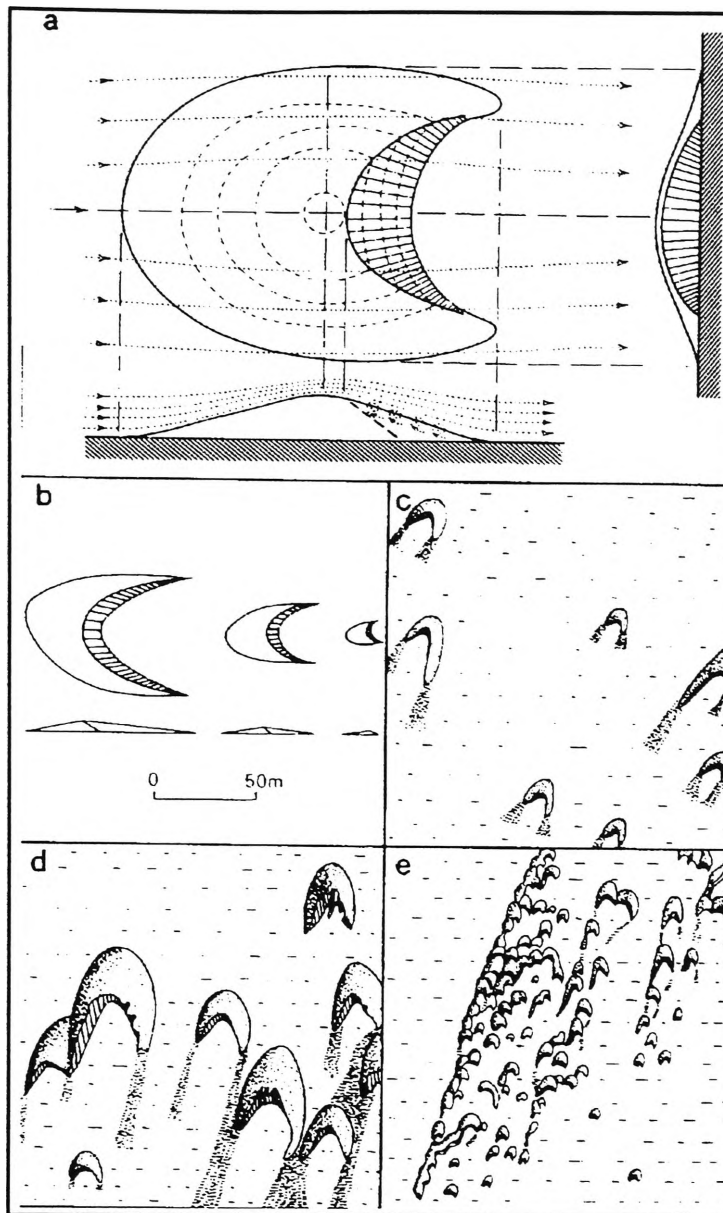
# LITERATURE REVIEW

### 2.1 GENERAL DESCRIPTION

In this section, the literature relating to the initiation, morphology, and the dynamics of flow over barchans and domes is reviewed.

Barchan dunes are crescentic shaped dunes, occurring as discrete forms in many deserts around the world (Figure 2.1). Their initiation, formation, evolution, and physical characteristics have been discussed by various research workers (Bagnold, 1941; Petrov, 1976; Allen, 1968; Cooke and Warren, 1973; McKee, 1979; Mabbutt, 1977).

Barchan dunes generally occur in areas of unidirectional winds and low sand supply, particularly on flat areas, such as gravel plains. They are seldom initiated on artificially smooth surfaces (Cooke et al., 1993). They are transverse in form, and characterized by two slopes. The windward slope maintains a  $15^{\circ}$ - $20^{\circ}$  angle, while the steeper lee slope, or slipface, maintains a  $33^{\circ}$ - $35^{\circ}$  angle (Petrov, 1976). Barchans are characterized by the 'wings', or 'horns' which give these dunes their classic crescentic shape, a form which is maintained as the dune migrates. Sand is transported downwind from dune to dune. If the sand supply is uneven, or obliquely directed towards the dune, it may assume an asymmetric shape, with one of the wings, or horns, extending further downwind than the other, resulting in an asymmetric shape (Figure 2.2) (Allen, 1968; Mabbutt, 1977). However, some asymmetric dunes co-exist with those of 'classic' symmetry, implying that the above-mentioned factors do not adequately explain why some dunes develop an asymmetric morphology (Cooke et al., 1993).



**Crescentic dunes or barchans:**

**a = idealized form showing approximate wind distribution**  
(from *Bagnold, 1941*).

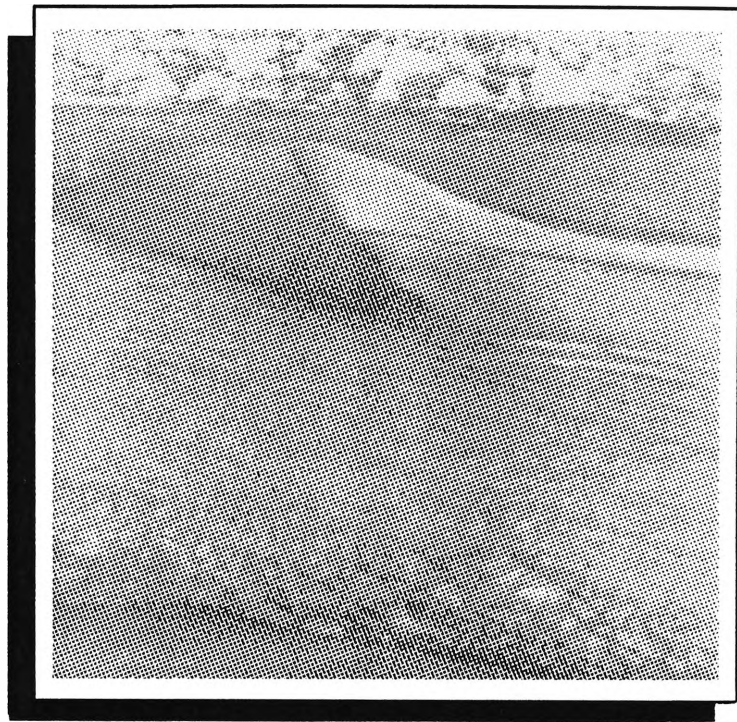
**b = relationship between dune size and plan form exemplified**  
by Peruvian dunes (from *Hastenrath, 1967*).

**c = sand streamers, sand shadows and variable symmetry**

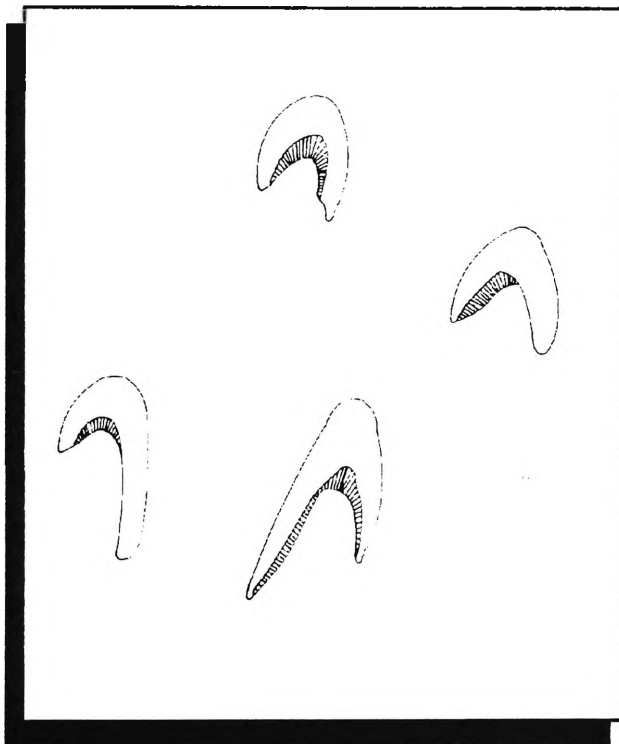
**d = barchans linked along streamers**

**e = compound barchans in a chevron patterns showing greater**  
sand supply from the left (figs. c-e from *Clos-Arceud, 1969*).

**Figure 2.1 Type of barchans**



Walvis Bay #1, 20 October, 1989



Asymmetrical barchans  
(from Clos-Arceud, 1967).

Figure 2.2 Examples of asymmetrical barchans

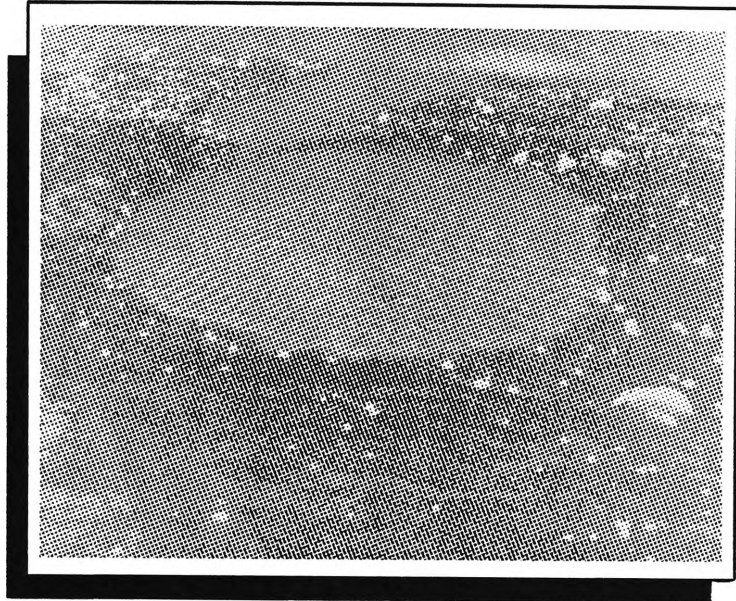
Dome dunes are also termed 'sand patches' or whalebacks (Bagnold, 1941; Allen, 1968; King, 1918) and are characterized by even slopes and a reasonably rounded profile (Figure 2.3). They do not develop slipfaces, and occur as discrete elliptical or rounded forms. Dome dunes develop in the upwind areas of many dunefields where winds are sufficiently strong enough to retard the development of a slipface (McKee, 1979), in the downwind end of dunefields where sediment supply is limited or wind fields are low (Bagnold, 1941). Figure 2.4 summarizes the characteristics of both domes and barchans, in addition to a variety of other dune types.

## 2.2 INITIATION AND MORPHOLOGY

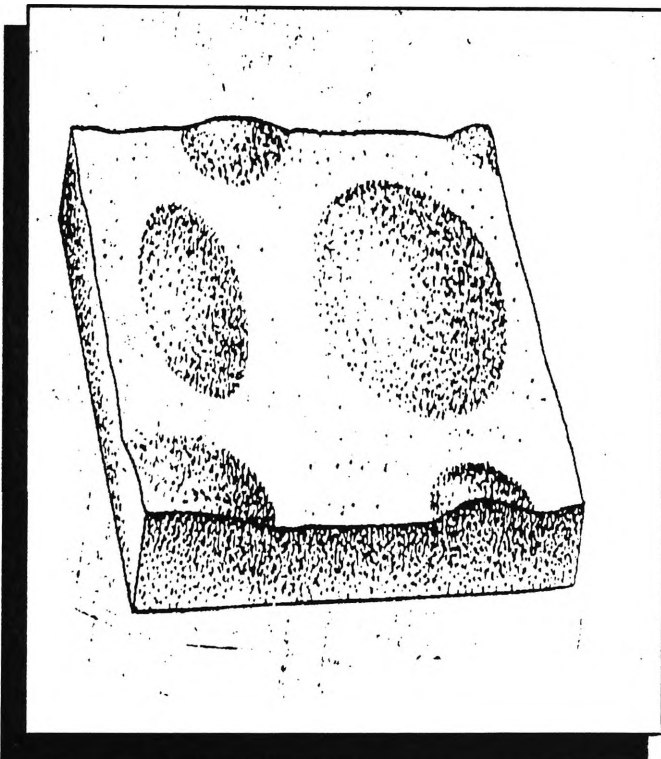
### 2.2.1 Barchans

Many theories have been postulated for the initiation of barchans. Bagnold (1941) describes the first phase in the initiation of barchans as being the deposition of a small patch of sand across the wind, with no lateral variation in sand supply. Wind initially streams across the patch as unseparated flow. The wind velocity at the edges of the patch is higher, due to the lower drag. Sand transport is more intense across the middle. With continued sand flow, the patch will increase in size and ultimately oversteepen near the crest. The oversteepening affects windflow, whereby the higher slipface allows the area of maximum deposition, i.e. the lee slope, to be increasingly sheltered, and deposition is enhanced. Flow separation occurs once the slope angle of a substantial part of the leeward side exceeds  $5^{\circ}$  (Allen, 1968) and the leeward slope becomes steeper until a slipface forms. At the maximum angle of repose ( $\sim 32^{\circ}$ - $34^{\circ}$ .) the mass of the slipface shears away and avalanching occurs, as the slope attempts to maintain this angle (Bagnold, 1941). The wings of the slipface advance downwind faster than the higher centre, until they enter the wind shadow of the dune crest, resulting in the crescentic form (Mabbutt, 1977). Mabbutt also suggests that dune height is consistently about 1/10 of the






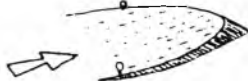









Dome dune, Cactus Beach, South Australia  
January, 1989.



Dome dunes  
(from McKee, 1979)

Figure 2.3 Examples of dome dunes

Dune type		Number of slip faces	Major control on form	Formative wind regime	Nature of movement
Zibar		0	Coarse sand	Various	Limited
Dome dune		0	"	"	"
Blow out		0	Disrupted vegetation cover	"	May extend down wind
Parabolic dune		1	"	Transverse. Unimodal	Slow, nose migration
TRANSVERSE DUNES					
Barchan dune		1	Wind regime and sand supply	"	Forward migratory
Barchanoid ridge		1	"	"	"
Transverse ridge		1	"	More directional variability than for barchans	"
LINEAR DUNES					
Linear ridge		1 - 2	"	Bimodal / wide unimodal	Extending
Seif dune		2	"	Bimodal	"
Reversing dune		2	"	Opposing bimodal	May migrate if one mode dominant
Star dune		3+	"	Complex. Multimodal	Vertical accretion

A classification of basic dune types (from Thomas, 1989).

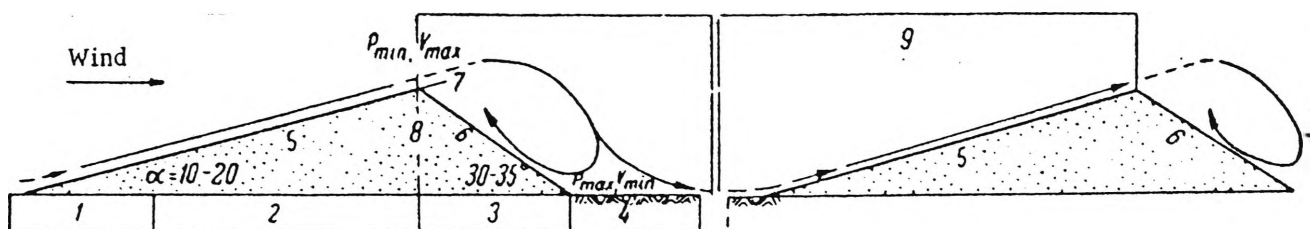
Figure 2.4 Basic dune types

width, and the dunes are mainly small. In addition, as size increases, dune shape is elliptical, with enclosed slipfaces, as in Peru, where downwind length averages three times the width. In Imperial Valley, California, the dunes are generally open forms in which the width may exceed twice the downward length.

Figure 2.5 illustrates the basic erosion and depositional patterns over barchans, as observed by Petrov (1976). Three primary zones are recognized: zone of removal (windward slope), transportation (crest area), and accumulation (lee slope/slipface). Specific flow characteristics are associated with these areas, and are briefly discussed here.

The windward slope represents an area of considerable change, and has a significant effect on sand transport (Cooke et al., 1993). There is a steady increase in velocity up this slope. However, prior to this increase, there is a marked decrease in wind velocity at the toe of the dune, and immediately upwind from it (Wiggs, 1993). This reduction in velocity is not accompanied by an observed increase in deposition; however, increased erosion up the windward slope does correspond with the increasing velocity. Shear velocity is such that eroded sand can remain in transport (Lancaster, 1987a).

At the crest of the dune, shear velocity is at, or close to, maximum. Some research has indicated that maximum velocity occurs just before the crest (Lancaster, 1987). The crest assumes variations in profile shape as a result of aerodynamic controls, with two end members: crest-brink coincidence, and crest-brink separation (Cooke et al., 1993). In this crestal area, sand is in transport, with no deposition due to the high shear velocity. Immediately downwind of the crest, velocity decreases suddenly, and is accompanied by deposition immediately over, and at the brink of, the slipface (zone of accumulation). Flow over the slipface is marked by separation and reversal. As erosion/deposition continues, the lee slope (slipface) periodically



Longitudinal profile of a barchan and its basic elements  
(from Petrov, 1976)

- (1) zone of removal
- (2) zone of transportation and exchange
- (3) zone of accumulation
- (4) neutral zone
- (5) windward slope
- (6) slip slope
- (7) crest
- (8) height of barchan
- (9) path of maximum sand saturation of wind sand stream

Figure 2.5 Erosional and depositional patterns over barchans

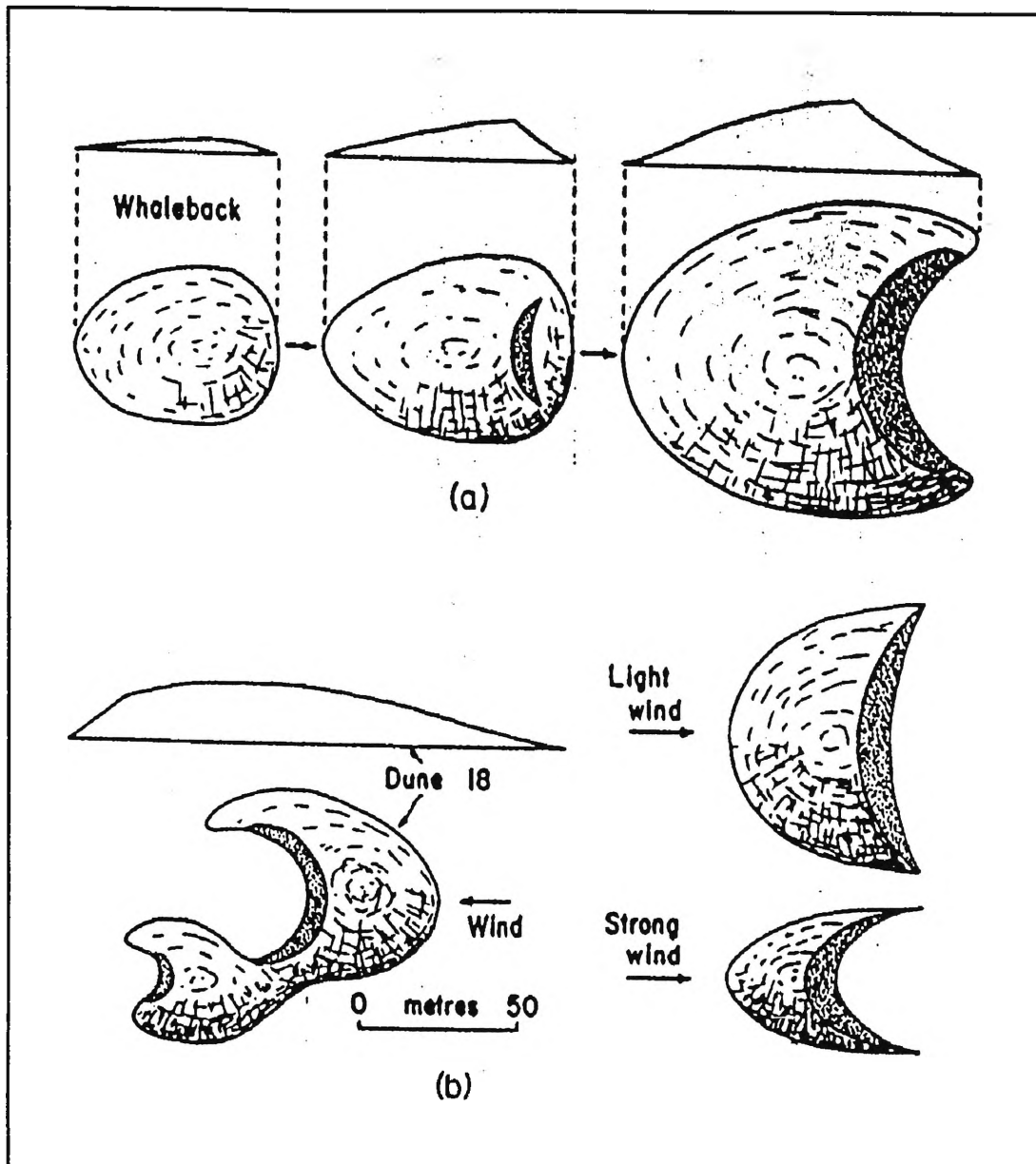
avalanches in order to maintain the 32°-34° angle of repose, as mentioned previously (Inman, 1966; Allen, 1968).

In addition to avalanching, sand is projected over the lee slope and may contribute to the formation of aprons (Cooke et al., 1993). Observations indicate that most of this grainfall occurs within the 'separation zone' and falls close to the brink of the lee slope, although during high wind events deposition may occur well outside this zone. A barchan maintains its form under these aerodynamic conditions by complex feedback mechanisms between sand transport, dune length, curvature and slope angle of the windward slope, and slipface height (Howard et al., 1977).

### 2.2.2 Dome dunes

Dome dunes often represent a phase of barchan evolution, and vice versa. Some research has indicated that a barchan may be initiated from a dome dune. King (1918), has described from surveys the sequence of forms through which a patch of loose sand (by definition, a dome) continues to evolve into a fully developed barchan (Figure 2.6). The first phase is represented by a low, rippled mound, oval in shape, which he refers to as a whaleback. The patch gradually increases in height relative to its length and the summit point, or crest, moves closer to the downwind end. This increase in height is accompanied by the development of a small slipface, which continues to broaden. The slipface begins within the bounds of the dome, but as growth continues, it moves towards the front of the dune, and gradually rests on the ground. Continued evolution produces the classic barchan shape.

Further evidence for the evolutionary relationship between domes and barchans is presented by McKee (1979). McKee trenched a dome dune in White Sands, New Mexico, and found that structures in the upwind side part of the dune consisted mainly of tabular-planar cross-strata,



Barchan dunes: sequence of forms (from King, 1918).

**Figure 2.6** Evolutionary sequence of dome (or whaleback) to barchan

with foresets dipping downwind at  $28^{\circ}$ - $33^{\circ}$ . In the downwind part of the dome, foresets dipped somewhat less ( $14^{\circ}$ - $27^{\circ}$ ). In a trench normal to the dominant wind direction, most of the stratification appeared to be horizontal or have very low dip towards the dune margins. McKee concludes that this dune type resembles other unidirectional wind deposits at White Sands, and states that the dome dunes probably began as barchans, if shape and structure can be used as criteria.

According to Cooke et al. (1993), the accepted definition for domes is synonymous to that of zibars. Zibars are without slipfaces, and comprised of coarse-grained (0.1 to 1.0 mm) sand (Nielson and Kocurek, 1986). However, dome dunes are distinct from zibars in the fact that they are built of fairly fine-grained, unimodal sand, usually within 0.1 to 0.3 mm.

### 2.2.3 Geometric relationships

One of the primary differences between dome dunes and barchans is the existence of a slipface. Barchans have fully developed slipfaces, whereas domes do not. The important basic elements of a barchan are its height, the angle of the slipface, and its crest (Petrov, 1976). Under a given wind regime and uniform grain size, the relationship between these elements should remain constant. In Peru, Finkel (1959) investigated the possible correlation between barchan height and the average width between the horns. His results are presented in Figure 2.7. His data show that a reasonably linear relationship exists between barchan height and distance between the horns. Support for the validity of this relationship is provided by Mabbutt (1977), who found that in the dunefields of southern Peru, dune height is consistently approximately 1/10 of the width between the horns. It has also been observed that the angle between the orientation of the barchan horns and the axis of the barchan is approximately  $55^{\circ}$ .

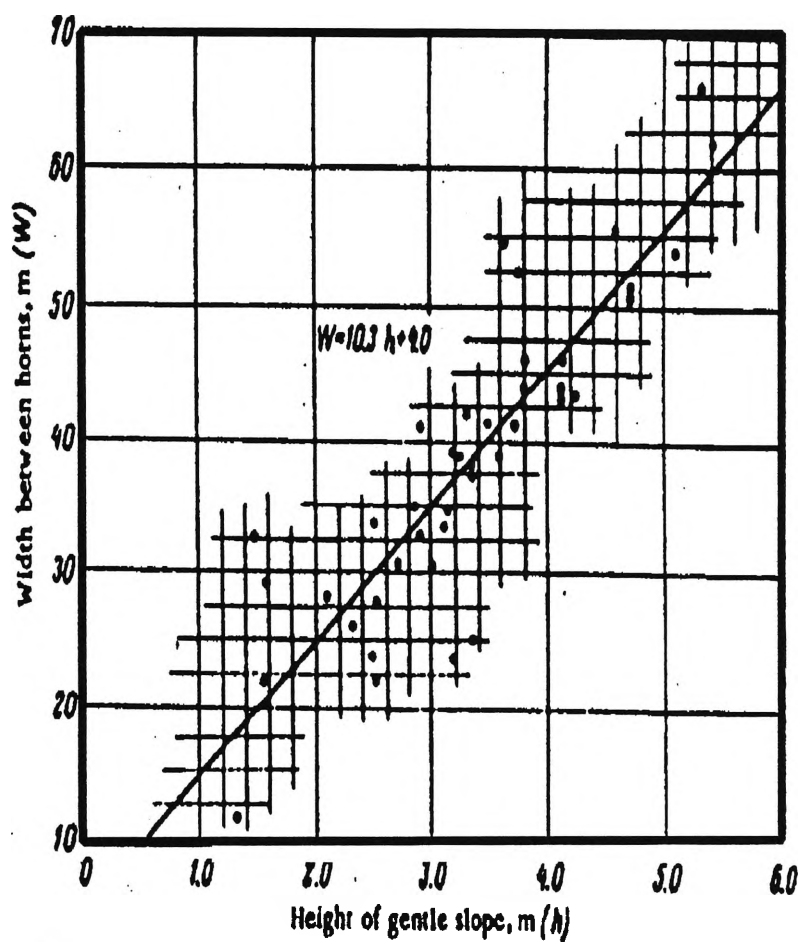


Diagram showing average width between horns of barchans as a function of their height (from Finkel, 1959).

Figure 2.7 Relationship between dune height and horn width  
Finkel, 1959



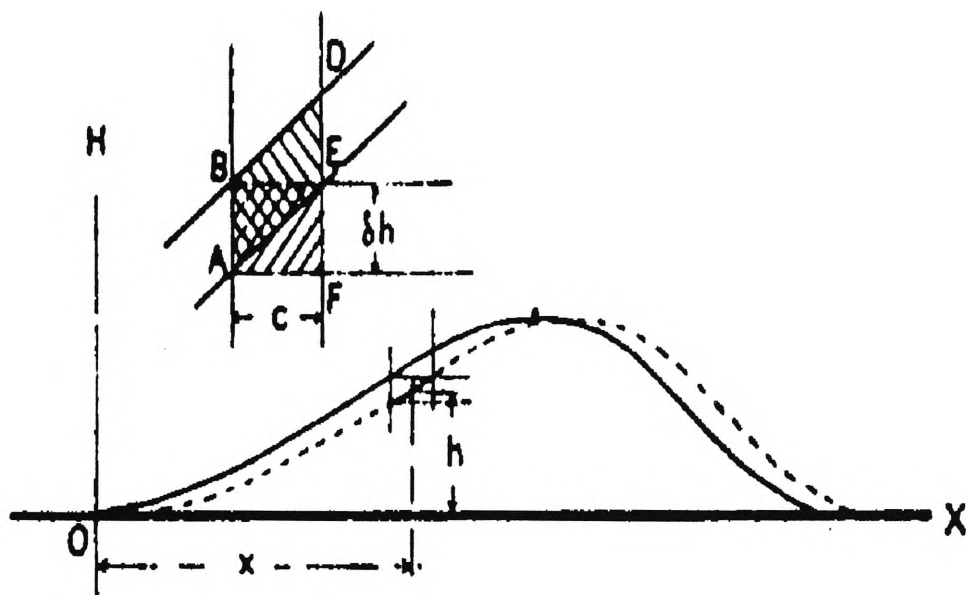
## 2.3 MIGRATION OF DOME AND BARCHAN DUNES

### 2.3.1 Introduction

Research on migration rates and the aerodynamic properties of dome dunes is limited. By contrast, research on rates of movement of barchans and flow patterns over the dunes has been extensive. That active barchans of different size, shape, and location travel at different speeds has long been recognized. Differences in local wind regime, sand supply, topography, and vegetation have some influence, but size of the dunes, especially height of the slipface, is generally regarded as the most important factor (Long and Sharp, 1964, p. 153). A review of literature dealing with the morphology of barchans, their aerodynamics and their rate of movement will be discussed in this section.

Migration of a sand dune in general terms has been described by Bagnold (1941). The rate of erosion is described as a function of a steady increase in velocity on the upwind slope, with a resulting increased sandflow and ultimately an increased rate of erosion. This rate of erosion is represented as the loss in a unit time from a unit area (Figure 2.8). In Figure 2.8, the rate of removal of the area  $AE$  is given as  $Q_e - Q_a$ ; if this result is denoted as  $dQ$ , then the unit time over which a weight of sand  $dQ$  is removed from the area is therefore known. The volume  $dQ/y$  represents the volume of this removed sand, with  $y$  being the specific weight of sand in bulk. This volume is represented by the parallelogram  $ABDE$ , which is equal in area to  $ABEF$ .

This relationship implies that, if the dune remains constant in shape, the sand which is transported from the surface between the levels of  $F$  and  $E$  will be equal in volume over the unit time. This transported distance is  $AF = c$ . This small difference of level can be called  $dh$ , and forms part of the relation:



Relations between rate of sand removal, rate of dune advance, and inclination of surface (*from Bagnold, 1941*).

**Figure 2.8 Dune migration**

$$dQ/y = cdh$$

**EF/AF** is equal to  $\tan dh/dx$  of the angle of inclination **a** at the point considered.

Substitution of  $dx \tan a$  for **dh** gives the equation:

$$dQ/dx = yc \tan a$$

**dQ/dx** is the rate of sand erosion or deposition per horizontal unit at any point. Positive values denote erosion, and negative values indicate deposition. From these relationships, Bagnold (1941) postulated the following theory:

"the rate of removal or deposition per unit area at any point on the surface is proportional to the tangent of the angle of inclination of the surface at that point"

(Bagnold, 1941, p.201)

From this relationship it is also apparent that:

(1) the rate of sand erosion or deposition will be constant over any area of the surface which lies at a constant angle;

(2) there can be no erosion or deposition at the crest where  $\tan a = 0$ ;

(3) where the surface angle is steepest, the transport rate is at a maximum (Bagnold, 1941)

These relationships do not take into account wind flow over the dune, as they are purely geometric. However, they do generally agree with the zones of erosion/transport/deposition over a barchan, as observed by Petrov (1976), in section 2.2.1.

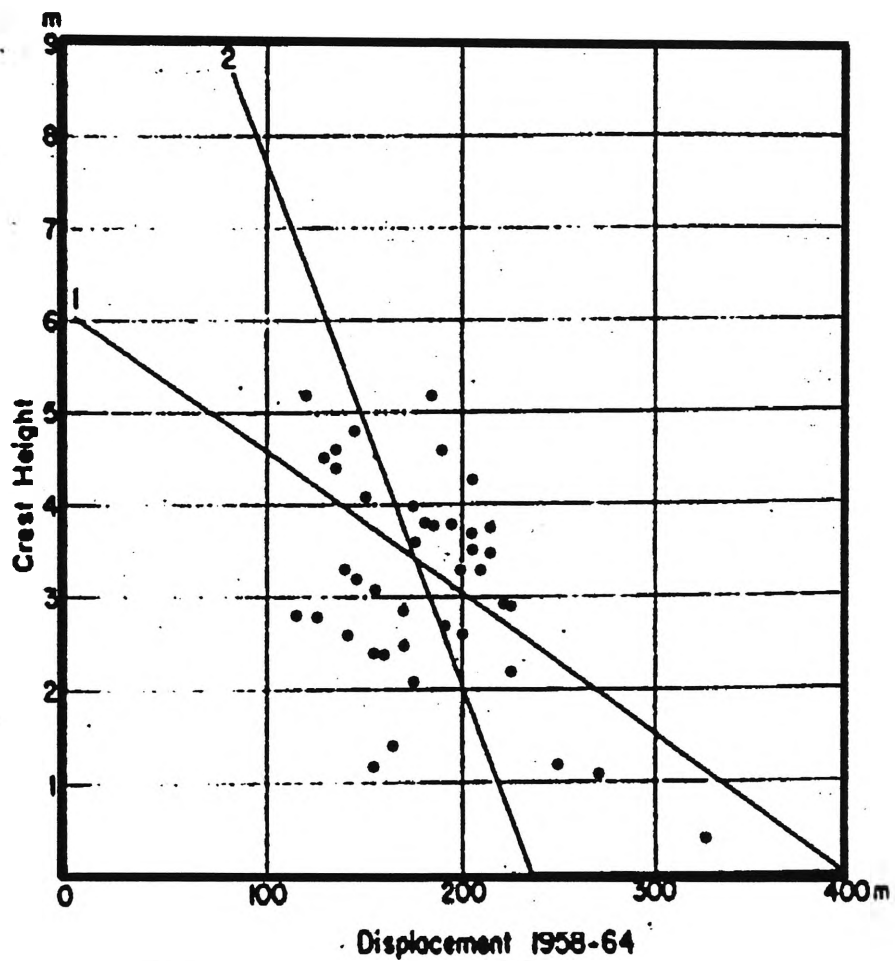
### 2.3.2 Migration of Barchans

Finkel (1959) studied the movement of barchans in Peru from 1955-58. As part of his study, he mapped displacement of 19 dunes from aerial photographs, and obtained heights for these dunes from field measurements. Finkel plotted the results of his study of barchan displacement as a function of height, and the reciprocal of displacement vs. height.

Finkel then decided to supplement the supposedly small sample size with data obtained from the aerial photo mapping. Horizontal displacement was measured for 75 more barchans. As the height of these dunes could not be determined from the map, they were deduced from measurements of the width across the horns, by means of a previously determined relationship (see section 2.2.3).

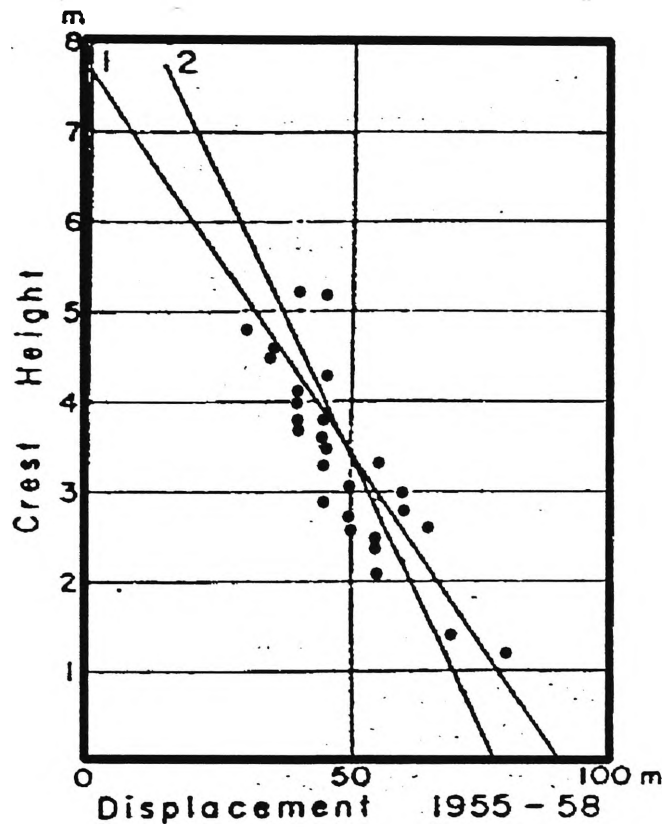
Hastenrath (1967) mapped 60 barchans in the Pampa de la Joya area of Peru. The entire dune area had been aerially surveyed previously by Finkel (1959). Both surveys contained vertical and horizontal ground control, which allowed the rate of dune movement to be calculated for the periods 1955-1958, and 1958-1964.

Hastenrath determined the existence of a relationship between crest height and total displacement, and concluded that smaller dunes travel faster than taller ones. Figure 2.9 illustrates the relationship between crest height and total displacement for the 1958-1964 period, while Figure 2.10 illustrates the same relationship for the 1955-1958 period. A comparison of the two figures shows that all the dunes surveyed during the 1958-1964 time



Relation between crest height (H) and total displacement (D) during the 69 month period 1958-64 (from Hastenrath, 1967).

**Figure 2.9 Relationship between crest height and dune displacement Hastenrath, 1958-1964**



Relation between crest height (H) and total displacement (D) during the 69 month period 1955-58 (from Hastenrath, 1967).

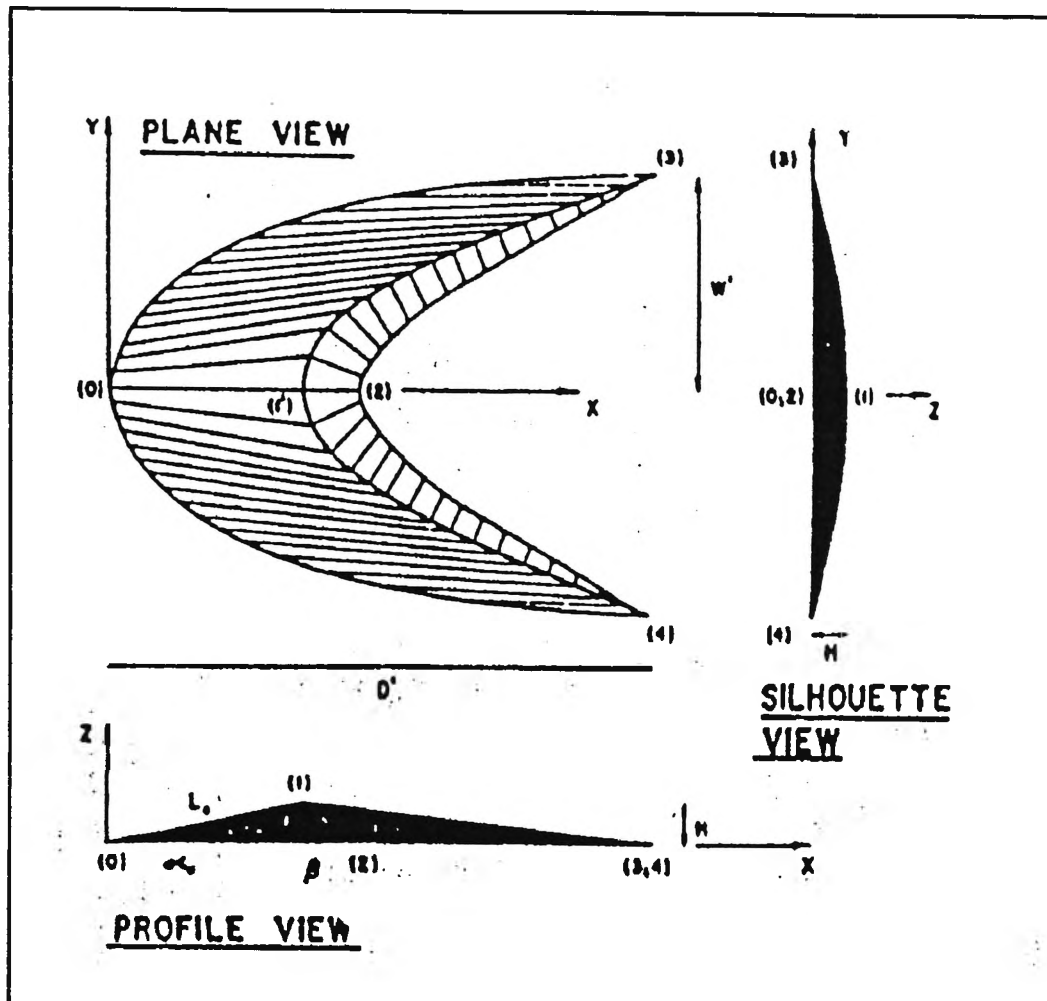
**Figure 2.10 Relationship between crest height and dune displacement Hastenrath, 1955-1958**

period travelled a constant amount of 22.6-41 meters/year faster than for the 1955-1958 time period.

Hastenrath (1983) again surveyed the Pampa de la Joya dunes in 1983, and found that the displacement rates for this survey period were similar to those of the 1958-1964 interval. The average crest height for the dunes decreased over the time period, which resulted in a corresponding flattening of the dune shape. This marked change in dune size without a corresponding change in displacement rate suggests a 30-40% decrease in sand transport. This decrease can be attributed to a number of factors, such as a decrease in sand supply, or change in wind velocity or direction.

The Pampa de la Joya dunes were also studied by K. and H. Lettau (1969). The aim of their research was to derive a quantitative estimate of bulk mass sand transport for 114 dunes over the same time period of Hastenrath's surveys (1964). The bulk mass transport was obtained as a sum of (1) annual mean celerity, i.e. the rate of migration in a horizontal plane, (2) dune volume, and (3) sand density. Volumes were calculated using the geometric parameters shown in Figure 2.11. These included total length (D), half width between the horn tips, the center value of the length of the windward slope ( $L_0$ ) and the x-axis, and the crest height. These geometric parameters were obtained from survey data collected by Finkel (1959) and Hastenrath (1964).

Results indicated that the average Pampa de la Joya barchan contained 685 cubic meters of sand. With a density of  $1.3\text{g/cm}^3$ , the total mass of the barchan amounted to 900 tons. The mean celerity was almost 30 meters/year. Therefore, the individual contribution to bulk volume transport in the region was  $20,550\text{ m}^3/\text{year}$ .



Schemes of barchan symmetry in plane, profile, and silhouette view (from Lettau and Lettau, 1964).

Figure 2.11 Geometric parameters for volume calculation



Lettau and Lettau (1969) observed that bulk transport first increased then decreases downwind. They also concluded from their data that the contribution from smaller dunes is considerably less than for larger dunes. They believe that this was important, as only larger dunes approximate the ideal barchan shape, and that smaller dunes are more irregular, an opinion shared by Hastenrath (1967).

Coursin (1964) measured forward displacement rates for barchans near Port Etienne (Algeria), using aerial photos from 1944 and 1954. The graphed results of displacement against height are shown in Figure 2.12. The symbols indicate the specific aerial photo data source of the data. The data illustrate a correlation between dune height and displacement. Dunes that have a greater height tend to migrate at a slower rate. The largest dune that Coursin measured contained approximately  $1,000,000\text{m}^3$  of sand, and was 31.4 meters high. It averaged an annual displacement rate of 15m/yr.

Long and Sharp (1964) also studied barchan movement in the Salton Sea, California (Fig. 2.13). They measured the displacement and the reciprocal of displacement of 47 barchans over three time periods from 1941 to 1963. For the period 1956-1963, the average annual displacement was  $\sim 27$  m/yr, while average displacement for the period 1941-1956 was  $\sim 17$  m/yr. Long and Sharp admit that these curves are "not good". They hypothesized that dune shape or location may in fact influence movement, given the poor results obtained from plotting dune height and displacement.

Long and Sharp (1964) also recorded the direction of migration and found a  $10^\circ$  difference in average direction of movement during the last seven years (1956-1963) compared to the preceding 15 years. Wind data collected in 1943 show that the wind direction was consistently from the west. Data from 1963 show that winds deviated from straight west no more than  $5^\circ$  on either side of west. They believed that it was difficult to accept that the wind regime had

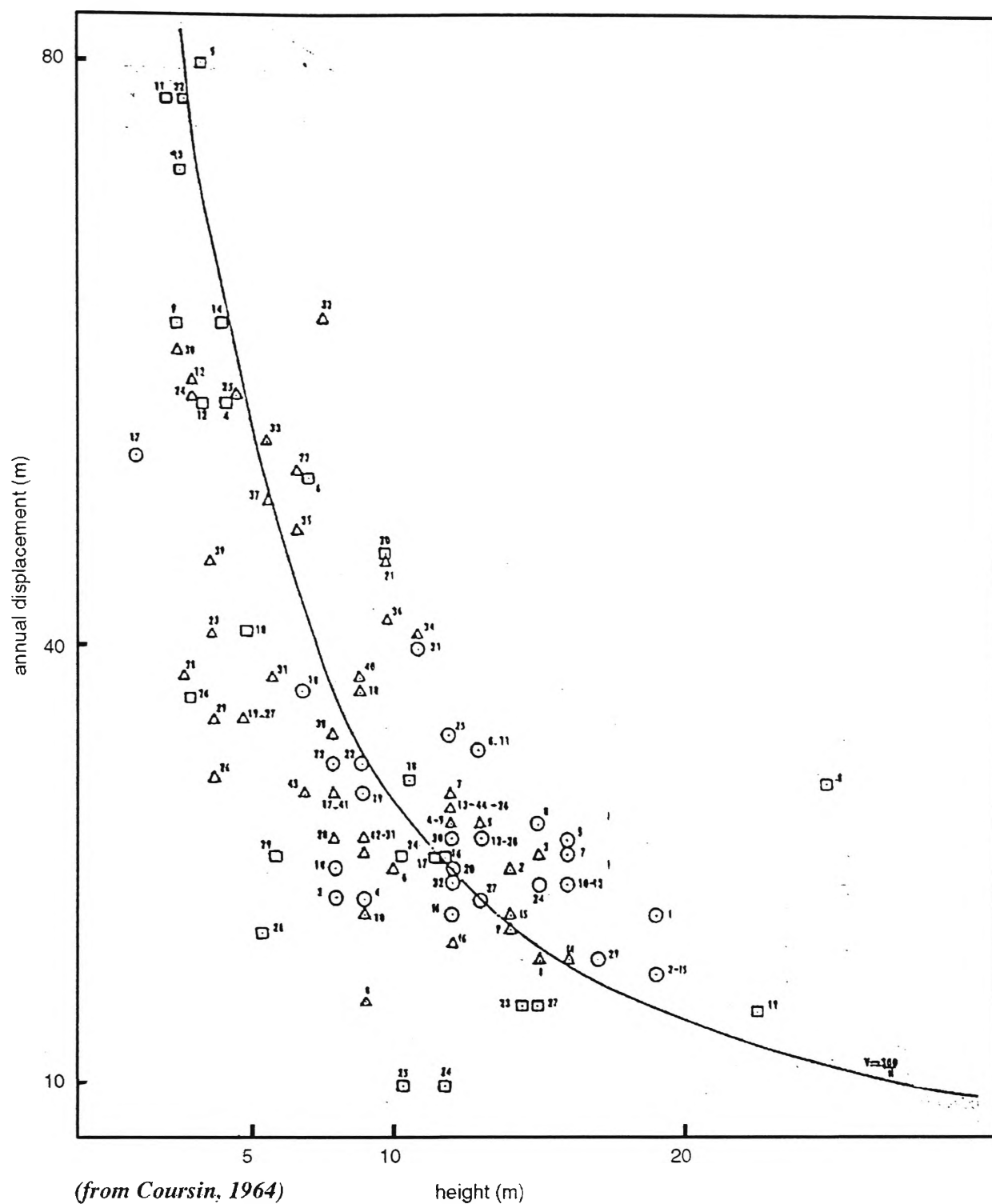
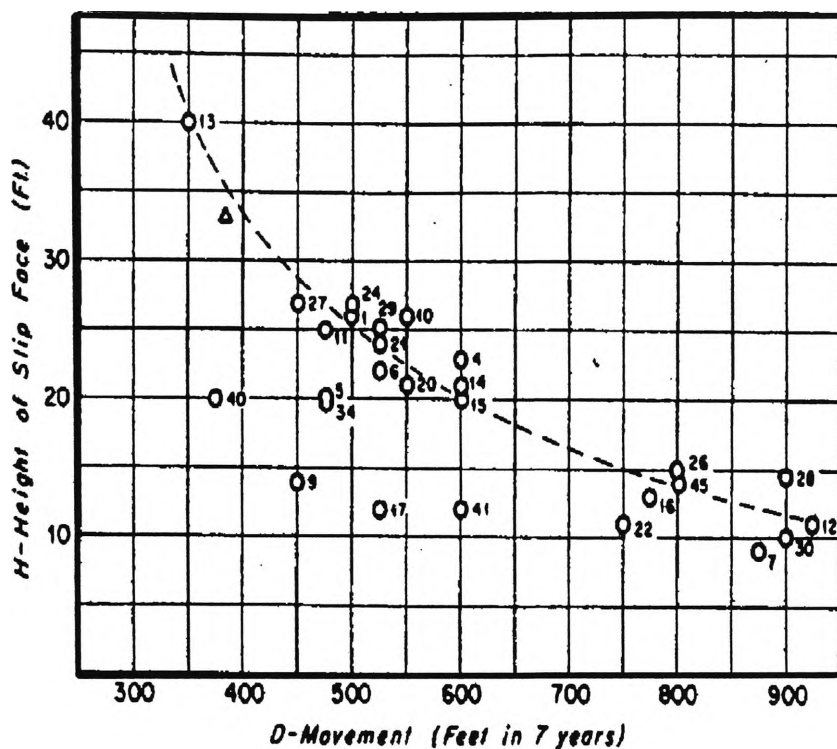
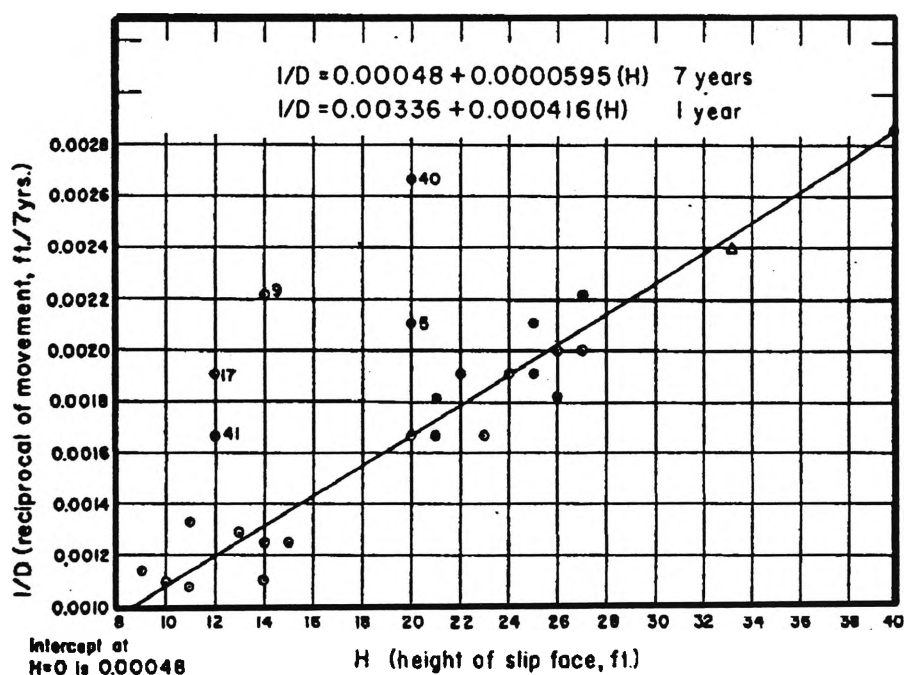


Figure 2.12 Forward displacement rate, Port Etienne barchans



Plot of distance moved (D) against height of slipface (H) for 27 barchans for 7-year interval, 1956-63 (from Long and Sharp, 1964).



Plot of reciprocal distance moved (1/D) against height of the slipface (H) of 27 barchans for 7-year interval, 1956-63 (from Long and Sharp, 1964).

Figure 2.13 Relationship between dune height and displacement  
Salton Sea barchans

changed to that extent over the 20 year period to cause a  $10^\circ$  shift in direction of dune movement, despite the data.

A possible influence on dune migration is dune shape. The relationship  $a/c$ , i.e. dune length  $a$  over distance between the horns  $c$  was plotted against movement without convincing results. Long and Sharp therefore hypothesized a relationship between dune shape, dune volume, and its dynamic state. If a dune that is fat is growing, i.e. not in a steady state condition, given a uniform sand supply, it should move more slowly than a growing barchan that is slim, because a greater volume of sand is required to produce a corresponding increase in height of the fat dune. However, in a steady state condition, a fat barchan may migrate faster, since most of the sand causing advance is derived from its long windward slope. Therefore, dune movement must be recognized as dependent on a variety of factors, within the context of the inherently dynamic state of the dune. The effect of dune shape on migration suggests that changes in dune volume may also be an important factor in dune movement.

Norris (1965) also studied the Salton Sea dunes, in addition to the Algodones barchans and the Tule Wash barchans, all within Imperial Valley, California. He attempted to collect quantitative information on the relationships between volume change, variation in form, and rate of movement for barchans. His data show that small barchans move more rapidly than larger ones, and that volume changes within a dune will be accompanied by changes in the rate of advance. A relationship between migration and volume was established only when data were collected over long time periods (a year or longer). Irregularities in the wind also contributed to poor correlations in some instances. Short periods of high winds caused rapid rates of advance, somewhat independent of volume. Norris concluded that a dune migrates more rapidly when it is shrinking and more slowly when it is growing. This observation is consistent with hypotheses put forward by Long and Sharp (1964) and by various other authors, e.g. Hastenrath (1967), Lettau and Lettau (1969), and Coursin (1964).

Khalaf and Al-Ajmi (1993) measured barchan displacement in Kuwait, as part of a study of encroachment problems in the Umm Negga and Al-Huwaimiliyah area. Ten dunes in each area were selected for monitoring migration rates over an 8-month period. Their morphometric parameters were measured and their outlines were delineated using measuring posts. Their results, consistent with previous research, indicate that smaller dunes migrate at a faster rate than larger ones. They plotted the 'morphologic parameters' against the mean size and migration rate for the various parts of the dunes and calculated a correlation coefficient of  $r = 0.85$  (regression equation:  $y = 28.226 - 3.5486x$ ) where  $y$  = the distance travelled by the slipface and  $x$  = dune height.

Khalaf and Al-Ajmi also found that different parts of the dune travelled faster than others, which resulted in a change in morphology of the dune. They used a ratio of  $L/H$  (migration rate of the lee side of the dune/migration rate of the horn) to indicate the uniformity of movement. A result of '1.0' indicates that the whole body of the dune is moving with the same rate. The ratio will be less than one if the horns are faster than the lee sides and will be more than one if the situation is reversed. Plotting these data against grain size gives a 'reasonable correlation' ( $r = 0.55$ ), indicating that the coarser the grain size, the more uniform the dune movement.

The coastal sand dunes of Guerrero Negro, Baja California, Mexico, were studied by Inman et al. (1966). This area consists of a 40 square km area of 6m high barchans which were blown in from a barrier beach to form a region of sand dunes across the lagoon. During the 3.5 years of observation, the dunes advanced at a rate of 18m/ year. This equates with a sand discharge of 23 cubic metres of sand/m width/ year. It was calculated that this discharge acting over the 1800 year life of the barrier beach was shown to be compatible with the total volume of sand required to extend the dune field across the lagoon to the mainland. Inman et al. (1966) found that a difference in dune travel occurred between summer and winter wind regimes. The winter

travel velocity of the dunes, from October 1956 to February 1957, and December 1957 to March 1958, was 2.1 cm/day. The summer travel velocity, measured from February 1957 to October 1957 was 8.4 cm/day. The uniformity of dune height and spacing suggested that migration was constant throughout the dune field.

## 2.4 AERODYNAMICS OF FLOW OVER A VARIETY OF FORMS

The understanding of the development and evolution of sandy bedforms requires an understanding of the relationship between a dune form and the flow which initiates and maintains that form. Initiation of the bedform occurs as a result of deformation of a surface by a given force, such as wind. Surface instabilities arise under the influence of the deforming agent (Bagnold, 1941). These instabilities represent an adjustment to the changed flow conditions. The adjusted form will subsequently affect the flow patterns as the system attempts to reach a state of equilibrium.

Specific characteristics of wind flow are important in the quantitative study of flow over dunes and other bedforms. This section outlines the properties of flow that are relevant to the initiation and evolution of dunes, and will review some of the research on wind flow and its behaviour over a variety of relevant forms (dune and non-dune).

### 2.4.1 Fundamental Flow Behaviour and Structure

Fundamental to the study of flow is an understanding of the different types of flow, why they vary and how they are produced. In 1883, Osborne Reynolds observed the behaviour of dye in a pipe of flowing liquid. Sometimes the flow was laminar and sometimes turbulent. His observations of this phenomenon led to the discovery that a certain combination of the variables of density, dynamic viscosity, and velocity, for a given pipe diameter could produce laminar or

turbulent flow. It appeared that when a certain combination of these variables exceeded 2000, the flow became turbulent. This combination is known as the Reynolds number (Re) (Vogel, 1981):

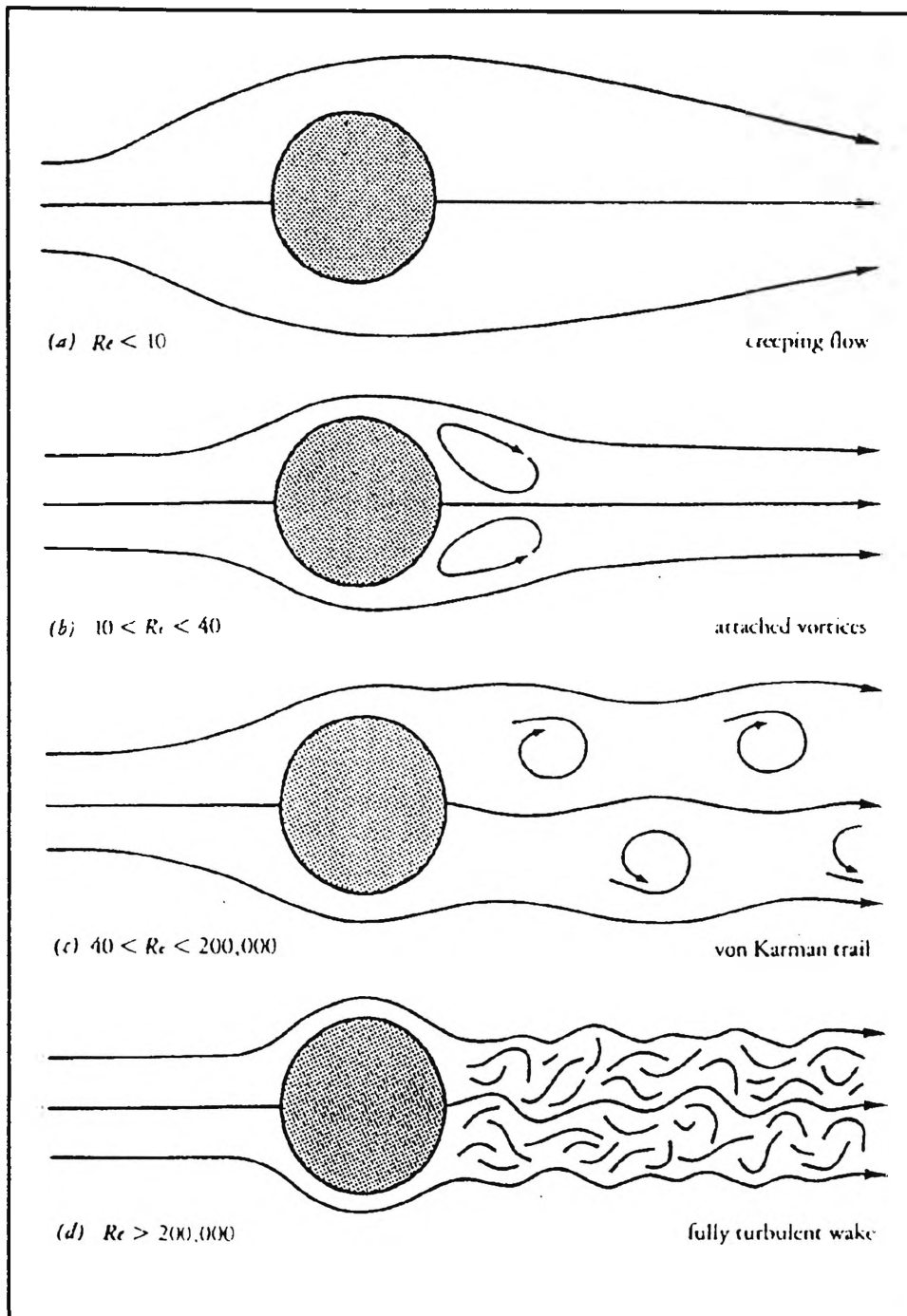
$$Re = \frac{\rho l U}{\mu}$$

with  $l$  representing the diameter of the pipe.

The study of flow around a cylinder has shown that at Re numbers well below unity, smooth, vortex-free flow is dominant (Figure 2.14). As the Re increases, eddies begin to form to the rear of the cylinder. At Re numbers above 40, flow is no longer stable and vortices alternately detach, producing a wake of vortices each rotating in opposite directions to the one preceeding it. The pattern of these alternating vortices are termed von Karman trails. At Re numbers above 200,000, the wake narrows and is dominated by fully turbulent flow.

At Re numbers well above unity, separation of flow results. Flow separation occurs as a result of pressure changes as flow moves over a cylinder; the pressure increases from front to rear. In the vicinity of the front stagnation point, the flow moves from high to low pressure. Beyond this point of minimum pressure, the flow must move against a pressure gradient at the expense of pre-existing momentum. The flow loses velocity due to viscous effects. At some point the flow stops following the surface of the cylinder and begins to flow straight downstream. This point is called the separation point, the location being Re number dependent. Downstream from the separation point, flow is turbulent and characterized by flow reversal (Vogel, 1981).

Many researchers (Allen, 1982; Leyton, 1975; Oke, 1978; Lee, 1987; Lawson, 1987; Marsh, 1987; Stull, 1988; Rifai and Smith, 1971; Bagnold, 1941; Hesp et al., 1989) have observed flow separation over dunes and similar forms. Wind velocity profiles and



Real patterns of flow around a circular cylinder. Note, in particular, the absence of any vortices at very low Reynolds numbers (a) and the constriction of the wake between (c) and (d). This last change is concomitant with the sudden drop in drag coefficient - the great "drag crisis" - at Reynolds numbers in the low hundreds of thousands (from Leyton, 1975).

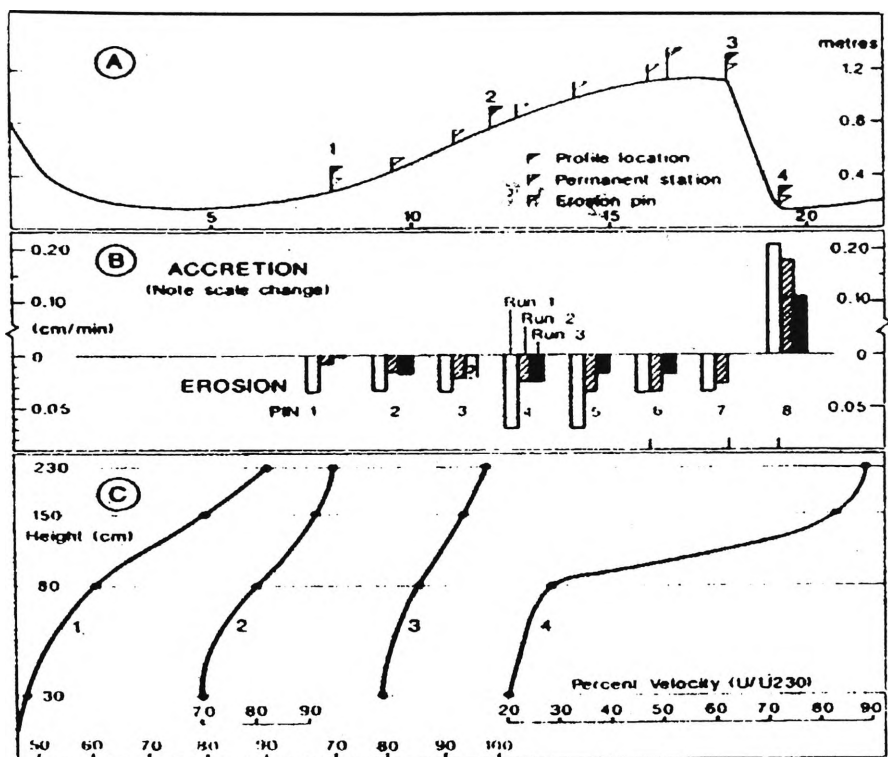
**Figure 2.14** Flow patterns around a cylinder



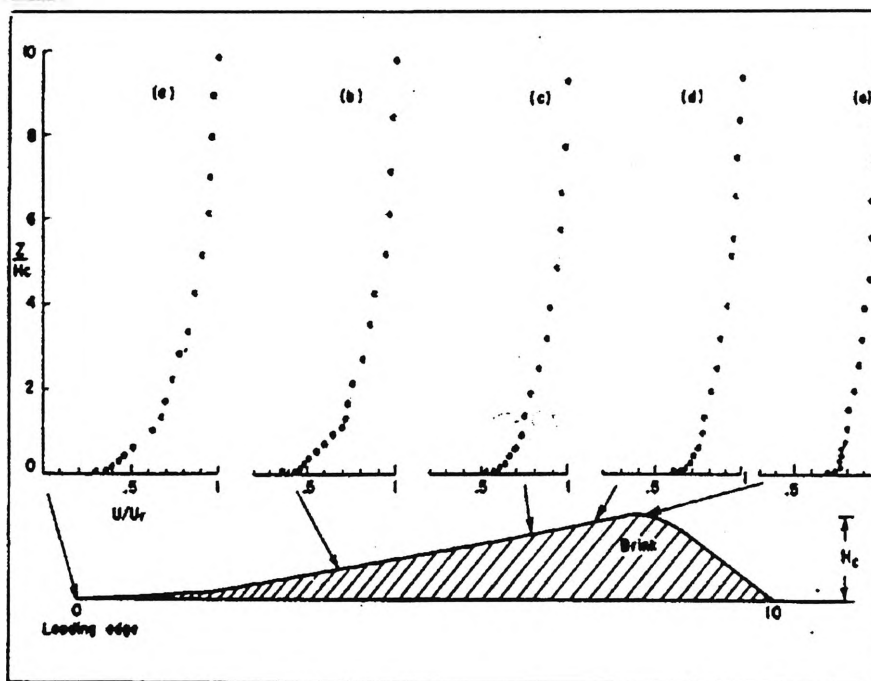
streamlines are commonly used to illustrate the phenomenon of flow separation (Figure 2.15). A streamline is a line whose tangent at any point in a fluid is parallel to the instantaneous velocity of the fluid (Oke, 1978). The wind velocity profiles demonstrate, by use of individual streamlines, how flow accelerates and is compressed at the crest of the dune. Separation occurs directly past this point and the occurrence of flow reversal is represented as a reversed streamline. This flow pattern is relevant to the study of sand dune morphology, as well as distribution patterns. The combination of the reversed flow region and the separated flow is associated with many sedimentary structures, and may contribute significantly to the determination of their geometry and often to the texture of the deposits marked by them (Allen, 1982).

In addition to the forms resulting from separated flow and associated drag forces, sand bodies subject to unidirectional flow may develop a streamlined shape. The tapered tail of a streamlined object produces a gradual increase in the pressure of the fluid, whereby flow remains attached over most of the surface. Once past the 'shoulder', fluid decelerates slowly and merges into the main stream, without forming significant eddies (Leyton, 1975; Vogel, 1981). Streamlining reduces drag only at high Re numbers. At lower Re numbers, the increased exposed surface area required for streamlining actually increases drag (Vogel, 1981). The high drag of forms such as cylinders and other bluff bodies can be reduced in some instances by roughening the surface. At high Re numbers, roughness actually increases drag, and at low Re numbers roughness is of little consequence. However, a range of Re numbers exists where increased roughness promotes small scale turbulence and can postpone separation as fluid moves down the body (Vogel, 1981).

According to Howard (1978), roughness may have an effect on dune size. Variations in roughness change the pattern of wind shear on the dune. Howard devised a model using sand transport equations and numerical simulations of turbulent flow by Taylor and Gent (1974) to



Example of velocity profiles over a transverse dune and associated erosion and accretion patterns (from Hesp et al., 1989).



Example of velocity profiles over a transverse dune (from El-Sherbiny and Bofah, 1982).

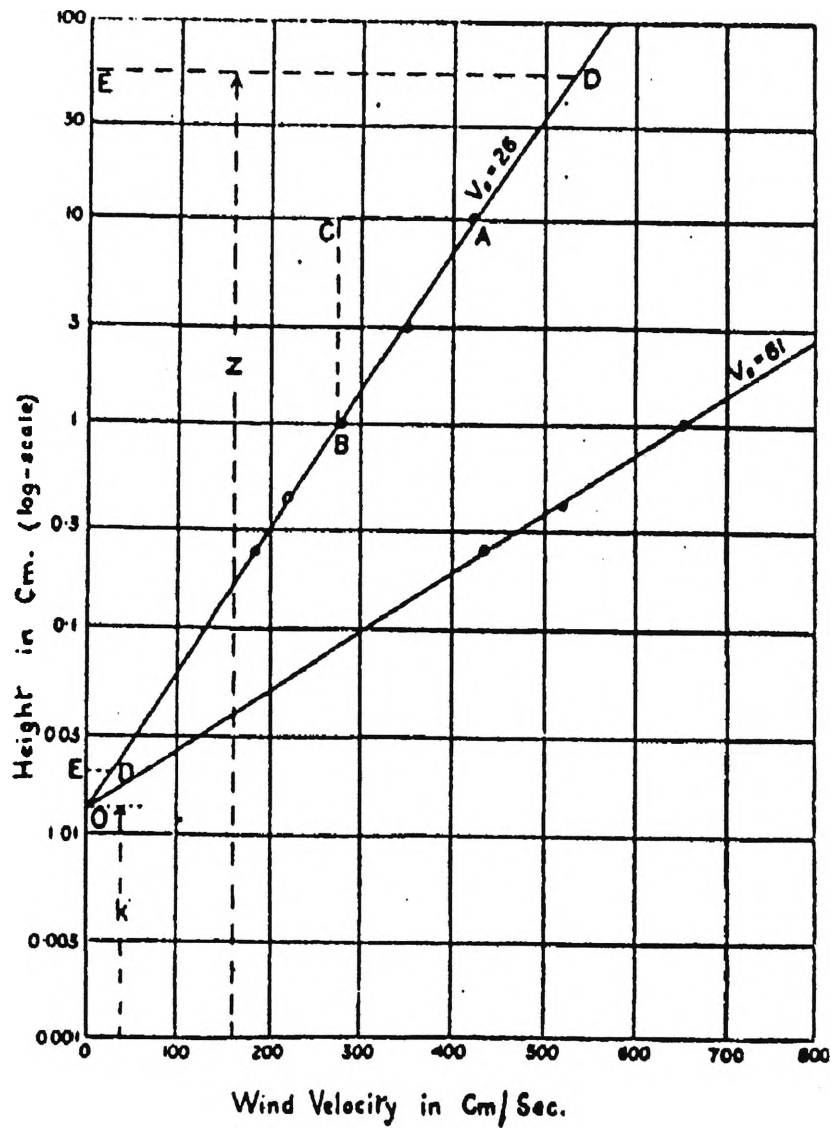
Figure 2.15 Examples of wind velocity profiles and streamlines

suggest that dune size is proportional to upwind roughness. If the upwind roughness is controlled by fixed roughness elements, such as a gravel plain or vegetation, then dune size, according to the model, would be larger. However, no systematic data are available on the correlation between size and upwind roughness.

Bagnold (1941) studied the relationship of wind velocity and surface roughness, and determined that over any given uniformly rough surface, the velocities of all winds at all heights reasonably near the ground can be represented by a group of straight lines which converge to a focus on the axis of a graph depicting height and wind velocity (Figure 2.16).

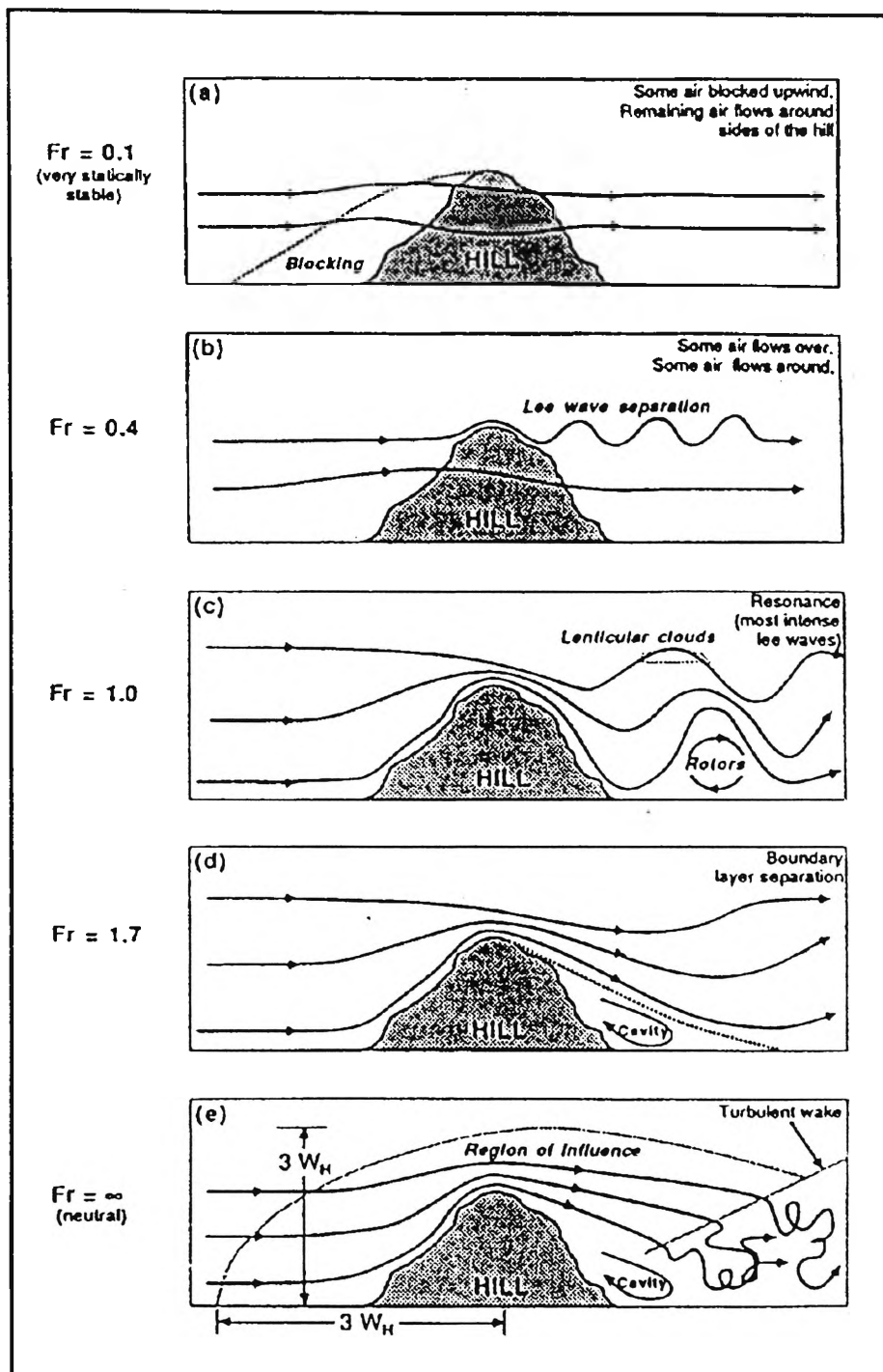
Another dimensionless number relevant to the study of aerodynamic properties of sand bodies is the Froude number. The Froude number represents the ratio of inertial forces to gravitational, or buoyant, forces. Hunt and Snyder (1980) modelled flow velocities over low hills. Their results indicate that higher velocities, as defined by the Froude number, will result in flow separation over two-dimensional hills of low- to moderate slope (less than  $45^\circ$ ). It was also observed that the character of the surface boundary layer flow is also a function of length of the hill rather than height.

Stull (1988) has also studied flow variation over low hills. His results were similar to those of Hunt and Snyder, whereby as Froude numbers increase, natural wavelengths increase to equal the size of the hill, and flow reversal begins to occur. Stull (1988) has studied flow patterns for a variety of Froude numbers, over an isolated hill (Figure 2.17). A low hill is a suitable form to use for flow modelling, as it is morphologically similar to that of a dome dune, or other low, rounded forms. In stable environments with light winds ( $Fr=0.1$ ), air tends to flow around a hill instead of over it. Directly upwind of the hill some air is blocked by the hill and becomes stagnant. This pocket of air combined with the hill itself creates a larger, more streamlined obstacle around which air must flow. Air will tend to flow over the top of the hill



Graph depicting the relationship between dune height and wind velocity (from Bagnold, 1941).

Figure 2.16 Relationship of wind velocity and dune height



Idealized flow over an isolated hill. The Froude number ( $Fr$ ) compares the natural wavelength of the air to the width of the hill ( $W_H$ ) (from Stull, 1988).

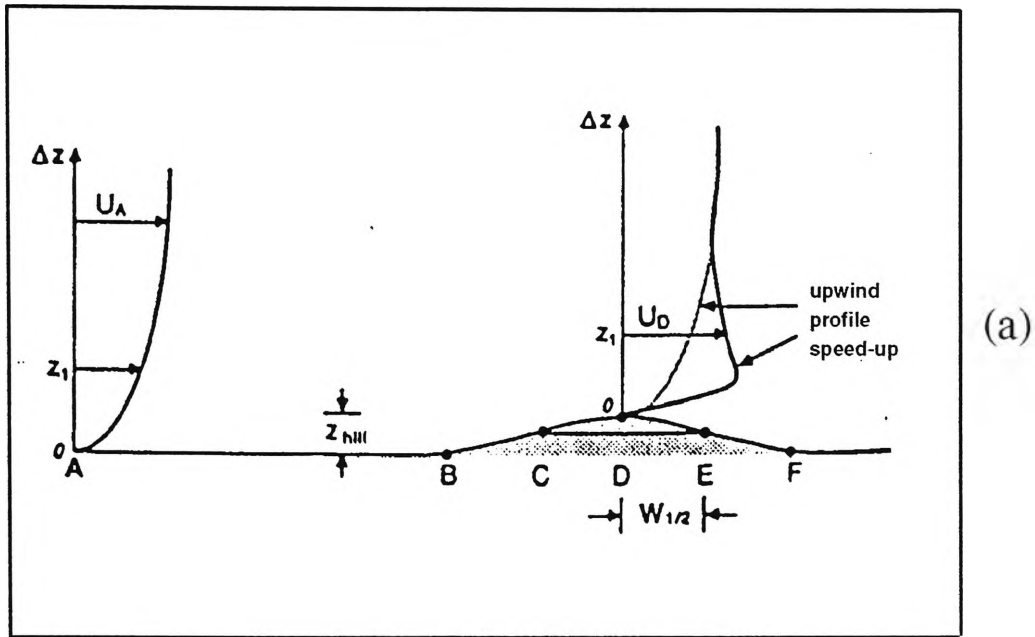
Figure 2.17 Flow patterns over an isolated hill

as well as around it with a Froude number of 0.4. Lee wave separation begins to occur, as air is perturbed by the hill. As the Froude number increases, natural wavelengths increase to equal the size of the hill. Flow reversal begins to occur, and with a Froude number up to 1.7, boundary layer separation in the lee of the hill creates a cavity of air with reverse surface wind direction immediately behind the hill.

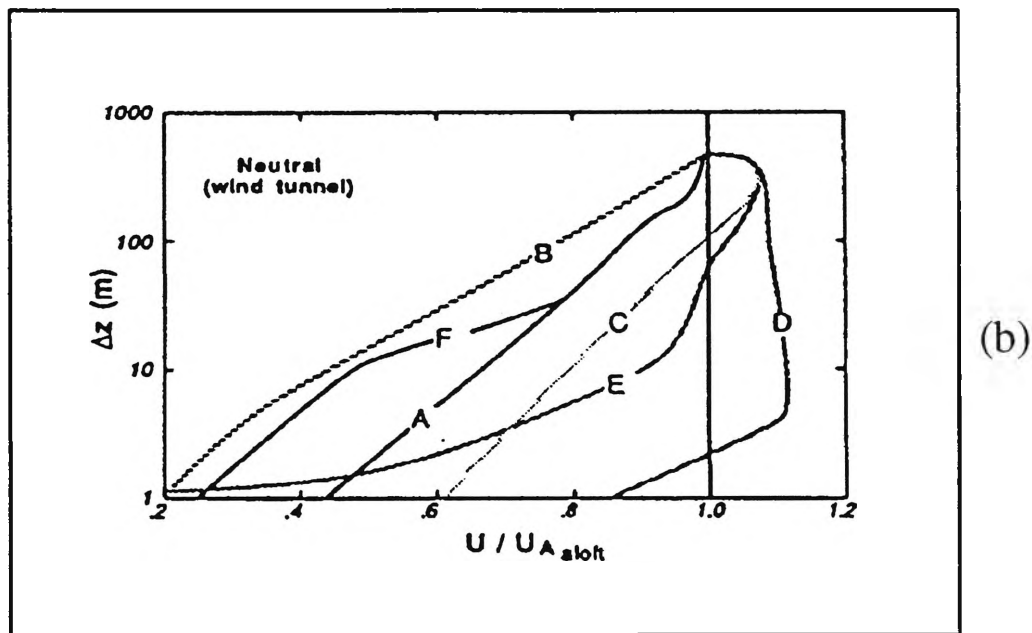
In strong wind conditions, wind velocity increases dramatically over the crest of the hill. This speedup is illustrated in Figure 2.18a. Teunissen et al., (1987) has simulated this flow behavior in a wind tunnel. Figure 2.18b shows the various wind speed profiles at different locations across a hill. At point A, well upwind, the profile is logarithmic with height. At point B, closer to the hill, some blocking is experienced and low altitude winds are slower. The winds above 2m, at point C, have accelerated beyond the undisturbed upstream values. Point D shows a rapid decrease in wind speed directly to the lee of the hill, and minimal flow reversal.

## 2.5 MODELLING OF FLOW OVER BARCHANS

Several researchers have attempted to model flow over barchans. Barchans are a simple discrete form and are therefore preferred for use in modelling sand transport and flow. Much emphasis has been placed on the use of models to simulate real world conditions because models allow constant visualization of processes under set conditions, and control of a range of variables which cannot be held constant in the field. Whilst neither laboratory nor computer simulation modelling were undertaken as part of this thesis, much of the research in this area is relevant to the understanding of field-based processes. The following section presents a brief overview of some recent work.



Sketch of wind speed-up over a gentle hill (from Teunissen, et al., 1987).



Wind tunnel simulation of the wind profiles over a hill, at the stations labeled A through F on Fig. 2.18 a (from Teunissen, et al., 1987).

Figure 2.18 Simulated flow behaviour over a hill

### 2.5.1 Simulation models

Howard et al., (1978) attempted to develop a simulation model of erosion and deposition across a barchan under a unidirectional wind regime. A representative barchan in the Salton Sea dunefield was used to obtain data on dune geometry, sand transport, and wind flow. This data was used as a modelling base and ultimately utilized to verify the model. The results indicated major discrepancies between observed and simulated erosion and depositional rates in various areas of the dune, particularly near the toe of the stoss slope and along the wingtips.

In 1985, Howard and Walmsley developed a simulation model for aeolian deposition and erosion on three dimensional sand bodies. The model was designed for investigation of wind and sand transport interaction, the primary controlling factors of barchan size and shape. However, the model developed numerical instabilities over time, which significantly reduced its viability. However, "despite the systematic discrepancies between simulated (or predicted) erosion and deposition rates due to variations in direction of the oncoming wind, the model sufficiently reproduces the predicted rates" (Howard et al., 1978, p. 40). This model also showed that variations in slope morphology affected erosion and deposition patterns, results which were confirmed by field observations.

A computer model of barchan evolution and migration has also been developed by Wipperman and Gross (1985). Wipperman and Gross (1985) appear to have developed a reasonable model of flow behaviour over a barchan, and also its initiation and evolution over time. Occasionally the model indicates questionable flow conditions (over the lee slope) and some of their data do not appear to equate with field observations.

The model also assumes that a conical pile of sand will develop into a barchan dune. Field observations have not shown this to be necessarily true. Lettau and Lettau (1978) conducted



limited experiments with conical piles of sand of varying volumes. After a period of sand moving winds, all cones had developed into elongated humps with well-defined crestlines. The dunes were observed over the next two days, and during this time the leeward section never became steep enough to be classified as a true slipface.

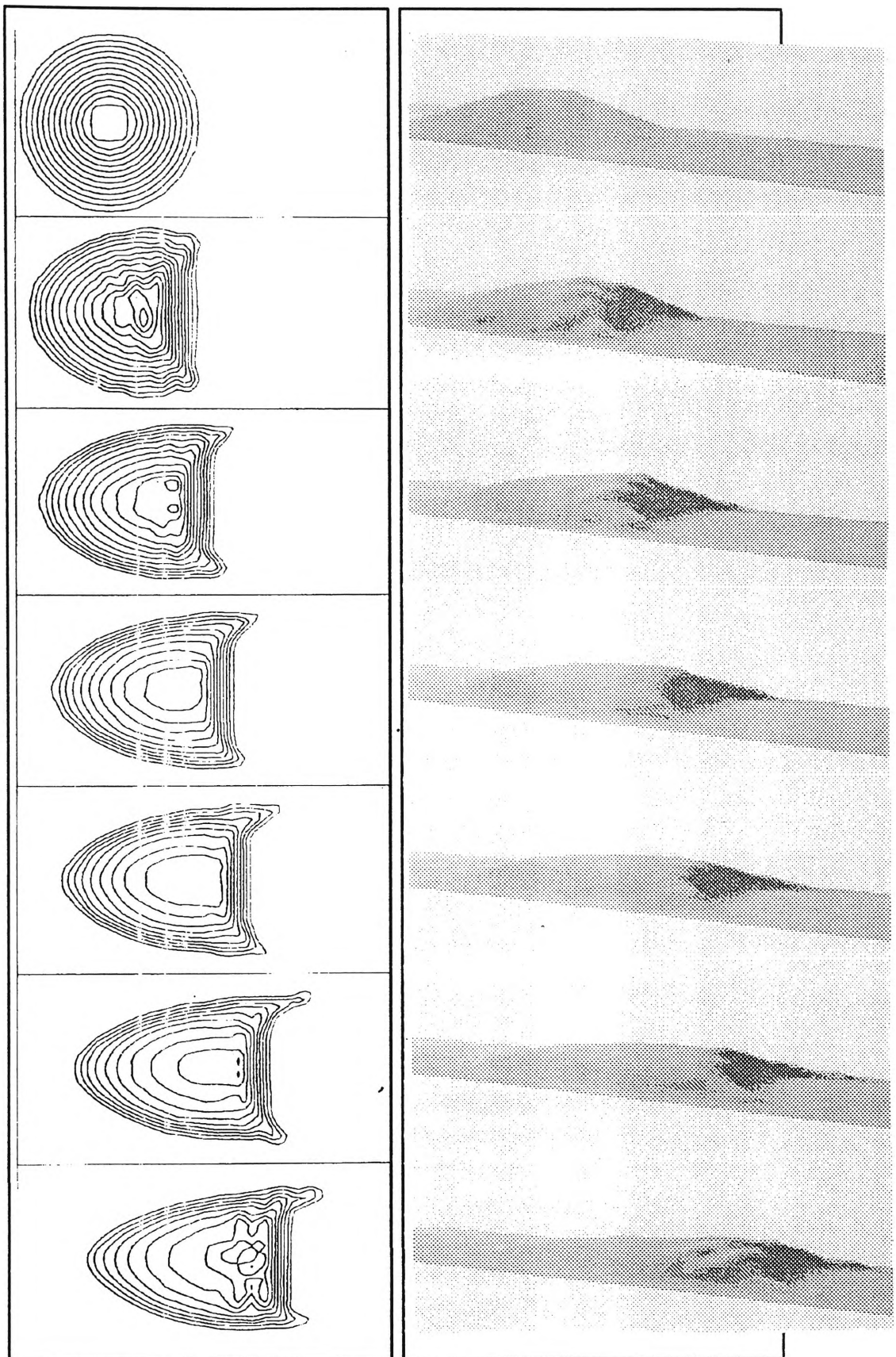
Flood (1991) modelled flow over both a 2D and 3D mound (Figure 2.19 and 2.20) Flood's model is in good agreement with field observations, and represents the best example to date of both 2D and 3D flow modelling over a transverse dune. The 'flow model, in combination with a Bagnold-type sand transport equation, is able to simulate the shaping and migration of realistic dune forms' (Flood, 1991, p. 83).

## 2.6 CONCLUSION

An overview of the literature indicates relatively consistent theories and observations exist on barchan initiation, morphology, and the flow patterns associated with the form. There is a distinct lack of detailed research on dome dunes, aside from a recognition of their role in the dome-barchan evolutionary process. As Allen (1982) acknowledges, dome dunes represent a form which is relatively aerodynamic; as such, they do not pose any difficult questions to those who wish to model complex flow patterns.

At present, the literature indicates the following:

(1) the initiation and morphology of barchans and domes is well-established. The evolutionary relationship between these two forms is also recognized, although there have been limited field observations of the process.



Shaping of a 3D mound. Initial mound of sand on rock basement, with incoming wind carrying no sand (*from Flood, 1991*).

Figure 2.19 and 2.20 3D flow modelling

(2) migration rates of barchans have been shown to be strongly related to dune size (height). This relationship has been consistently observed over long-term measurement periods. However, most of the research to date has not studied the validity of this relationship for short-term (days to months) measurement periods.

(3) wind velocity variations and corresponding erosion/deposition patterns over barchans have been measured. The importance of flow separation in the initiation/ maintenance of the dune form is recognized by all researchers. However, little research has concurrently measured flow patterns and sand transport rates over both a dune form with a slipface and one without a slipface to examine variations in flow conditions, dune dynamics, and the evolution of slipfaces.

(4) computer simulation and field-based models have used the barchan as a basis for studying flow over discrete forms. Most of these models have yet to accurately model observed morphologic changes, as they inevitably prove to be unstable. Despite this instability, the models included as part of this literature review provide information relevant to the dome-barchan evolutionary process, particularly the spatial distribution of erosion/deposition zones, and the resulting changes in dune morphology over time.

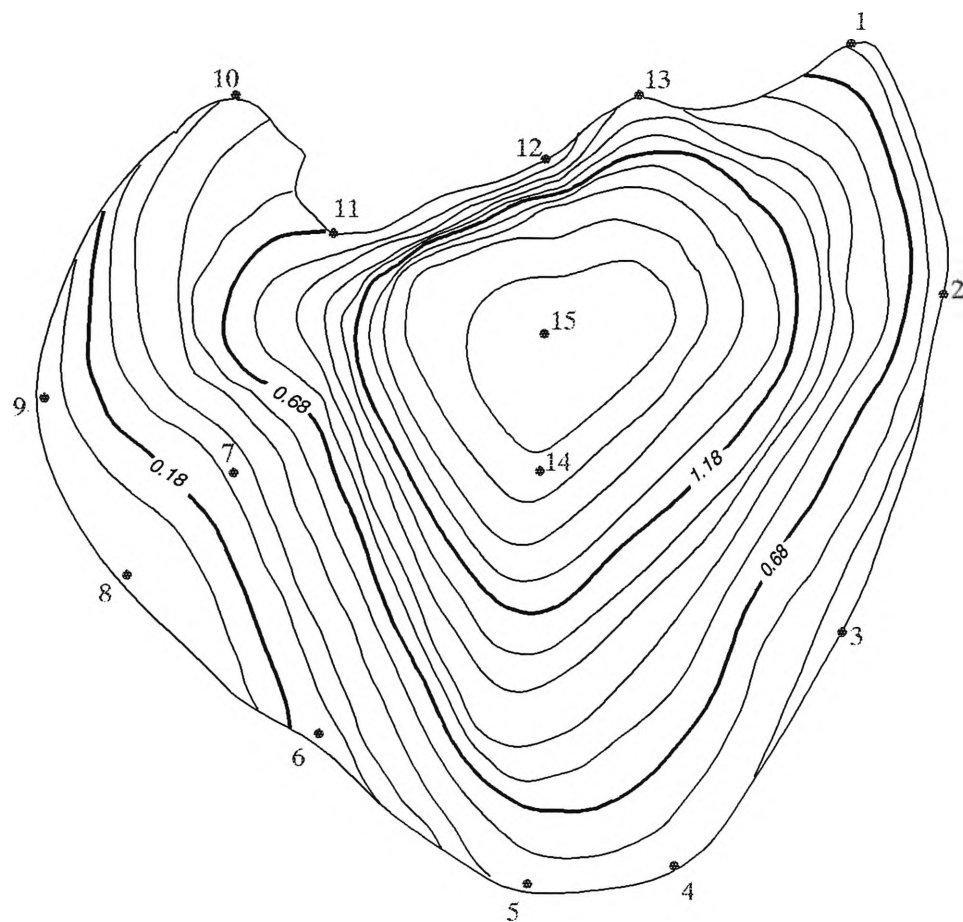
## Chapter 3

# METHODOLOGY

### 3.1 DUNE MORPHOLOGY AND MOVEMENT

Six dunes, three located south of Walvis Bay and three near Swakopmund, were selected and surveyed at approximately every two to three week intervals over the period July to October, 1989. Each dune was numbered and a series of star pickets was placed around the perimeter of the dune and also on the dune, to use as survey reference points and bench marks (Fig. 3.1). The pickets were numbered sequentially, with the total number dependent on the size of the dune.

The center line of pickets for each dune was set at a bearing of  $180^{\circ}$  for the purposes of topographic surveying using a dumpy level and four-meter staff. The dumpy level was positioned over the same picket at each survey period. This picket served as the benchmark for subsequent surveys and was given an arbitrary height value of 10m. All the subsequent survey points on each dune were calculated relative to this value. Each of the six dunes was surveyed seven times on or near the same day for a total of 41 surveys (Swakopmund #3 was surveyed only six times) over the period 7 July to 23 October, 1989. Each survey was carried out by surveying closely spaced radial lines on compass bearings extending from the standard bench mark to the edge of the dune. In this way a very detailed topographic survey of each dune was produced. Over time, the dunes migrated out of the initial perimeter of pickets, particularly the Walvis Bay dunes. However, the center line of pickets containing the benchmark picket was included in each subsequent survey as a baseline for calculating relative movement.



Walvis Bay #1  
Survey 1  
8 July 1989



0 5 m

Contour Interval = 0.1m

• 13  
Survey bench marks

**Figure 3.1 Example of survey point placement at the beginning of the survey period**

Contour maps at a 10 centimeter interval were hand plotted for each dune from the survey data (Appendix I). The original picket positions were included in each contour map as benchmarks. Calculation and comparison of dune movement between each survey period was made relative to these pickets.

### 3.1.1 Photographic Record

Photographs were taken of each dune at the completion of each survey. A selection of these photographs are presented in Chapter 4. Two photographic points were initially selected near each dune in an attempt to allow a comparison of morphologic change and direction of movement between surveys. The best overall view of the dune from the photographic point was obtained by standing on top of the vehicle as opposed to remaining at ground level. Although these photographs provide a "real picture" of the dunes, they are not particularly useful for accurate comparisons of movement, in part due to the technical limitations of the camera and the limited choice of suitable vantage points.

### 3.1.2 Dune Migration

For the purposes of obtaining an accurate measurement of dune movement, it was first necessary to locate a point consistently identifiable on each contour map. Movement could be calculated relative to this point with a reasonably high degree of accuracy. Initially, the base of the slipface was thought to be a consistent point easily recognizable on the dune and common to each map. This point is also the position used by all previous studies of barchan movement. However, over time the dune morphology changed significantly as dune orientation reversed or varied in direction, rendering accurate identification of the center of the slipface virtually impossible. It was then considered that the center of the dune itself would provide an accurate reference point. As with the slipface measurement, the consistent identification of the center of

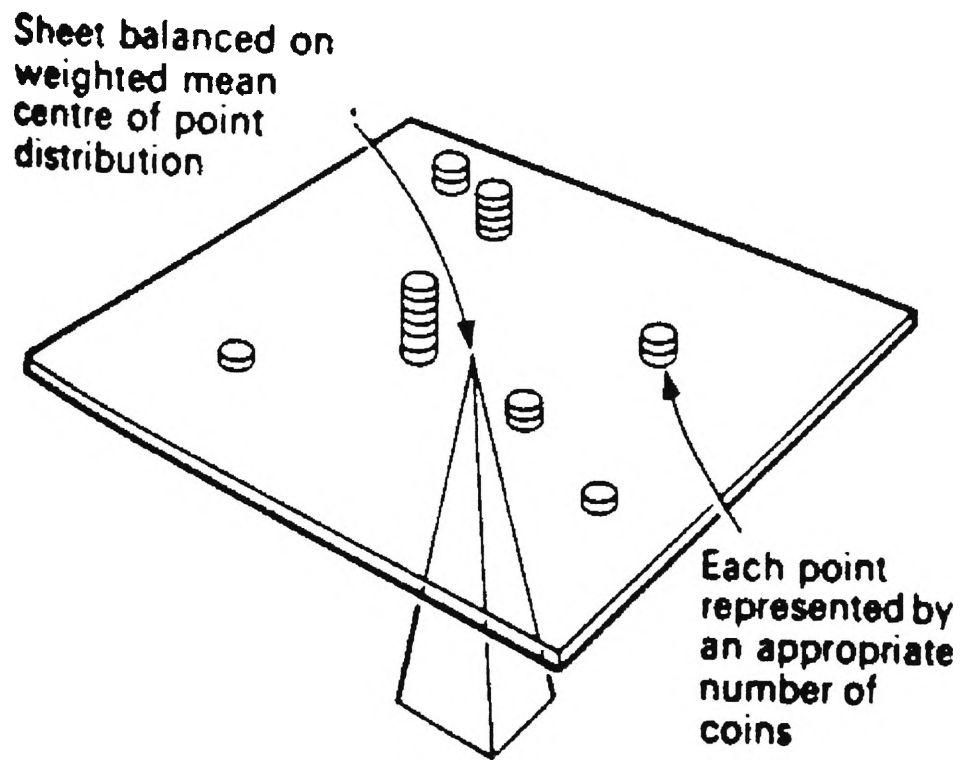
the dune was impossible due to continual variation in dune form over time. A simple method for determining the center was to draw a rectangle around the dune with each line tangent to a side of the dune. The center of this rectangle was taken as the center of the dune. A problem which made dune center determination by this method particularly difficult was the occasional elongation of one horn of a dune. When the tip of this horn was taken as the edge of the dune, the resulting center point was noticeably incorrect; occasionally, the calculated center point was completely off the dune itself.

Eventually a statistical method was employed to determine a reference point using Ebdon's (1985) formula for calculating the weighted mean center of a data set. A weighted mean center, as opposed to a mean center, allows each point to be assigned a value proportional to its importance (Fig. 3.2). The result may be expressed as the center of gravity of the spatial distribution of points. The three-dimensional nature of the dunes necessitated the use of a method by which the shift in sand distribution and subsequent shift in center of the dune was taken into account.

The equation for determining the mean center is:

$$x_w = \frac{\sum xw}{\sum w} \qquad y_w = \frac{\sum yw}{\sum w}$$

where  $x$  and  $y$  are co-ordinates of the plotted survey points taken from the graph paper,  $w$  denotes the numerical weight assigned to each point. In this case,  $w$  is the point height value determined from the contour maps, and  $x_w$  and  $y_w$  are the weighted means of these co-ordinates. Measurements between dune center points for each of the seven surveys were made



The weighted mean centre as a centre of gravity (*from Ebdon, 1985*).

**Figure 3.2** Example of weighted mean centre



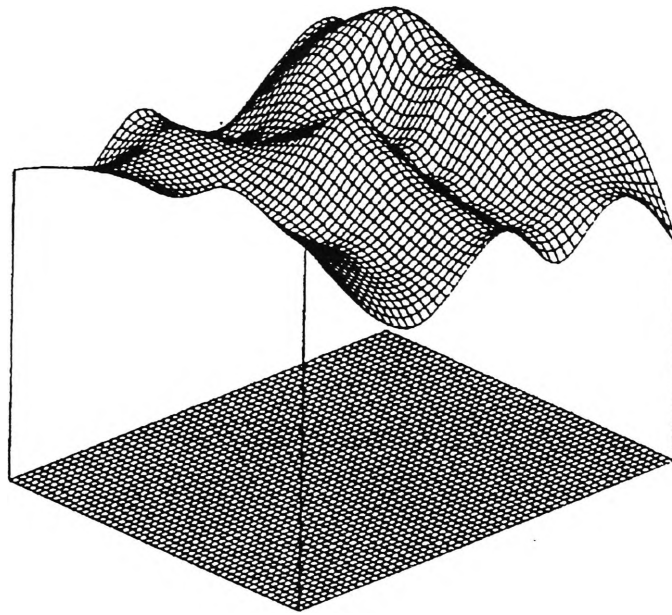
subsequent to the center calculation. The direction of movement was also noted. The results of these measurements are detailed in Chapter 4.

### 3.2 DUNE VOLUME

Volume calculations for each dune were made using a computer program called SURFER. This program allows computation of the net volume of a solid through three-dimensional integration. The solid used in the integration is defined by its upper and lower surfaces, either of which may be a gridded surface or a plane at a constant Z level. The data are used as X,Y,Z co-ordinates, defining the Upper Surface of the solid. The Lower Surface uses the default value of 0. The area between the Upper Surface Z value and the Lower Surface default value, at the given X and Y co-ordinates, is the volume of the solid (Fig. 3.3).

The input data for the calculation of the dune volumes are taken from the 41 contour maps produced from the original dune survey data. Each map was overlain with a metric grid which, when numbered, provided X and Y co-ordinates. Z values were obtained from the contours. Up to 350 co-ordinates were determined on the larger dunes.

SURFER calculates volume by three methods, namely the Trapezoidal Rule, Simpson's Rule and Simpson's 3/8 Rule. The results are given in cubic meters. According to the SURFER User's Manual, of the three methods, Simpson's 3/8 Rule is theoretically regarded as the most accurate. Simpson's Rule also gives reasonable results, but the Trapezoidal Rule should only be used to estimate the accuracy of these results. The absolute error for the results can be estimated by comparing the results of the three methods, using the difference between the largest and smallest results.



**Solid defined by a surface (UpperSurface) and a plane (LowerSurface)**  
*(from SURFER software manual).*

**Figure 3.3 Volume calculation**

The method assumes a flat surface as the basis for calculation, and measures the volume between the elevated surface (the dune surface), and the flat base. Given this methodological constraint, some error is to be expected in the volume calculations, assuming that the gravel plain upon which the dunes are located is not flat. Without knowing the exact character of the underlying surface, it is not easy to quantify this error relative to dune height. However, observation of this gravel plain has shown it to be reasonably flat, as the photos in Chapter 4 will indicate. Therefore, it must be assumed that the error inherent in these calculations is not enough to significantly affect the volume measurements.

The grid file created in SURFER for the purposes of volume calculations is also used to produce a three-dimensional and plan image of the dune using the TOPO and SURF commands. Prior to the creation of these images, separate posting files were produced for each dune. These files hold information which can then be appended to the grid files. Each posting file contained the location and number of the survey pickets. When the posting file information is appended to the plan map or the three-dimensional image, the result is a graphic representation of dune movement over the survey period, relative to the picket locations. These images are presented in Chapter 4.

### 3.3 FLOW EXPERIMENTS

Three separate flow experiments were conducted in August and October, over Swakopmund #1 and #3 (SW1 and SW3), to observe and measure flow characteristics over various dunes types and slopes. Measurements of sand transport were also taken. These experiments employed a series of micro-cup anemometers and erosion pins positioned across the dune. The methodological details of each of these experiments are included in Chapter 7, preceding the individual experiments.

In addition to these field experiments, a wind tunnel was employed to observe morphologic change under controlled conditions. The methodology and results of these observations are also included as part of Chapter 7.

### 3.5 WIND RESULTANTS

Regional wind data were obtained for two weather stations near both the study areas, for the 5-month survey period. Wind resultant diagrams and sand roses were produced from this data, using two methods (Landsberg/Jennings and Fryberger/Dean). This data were then correlated with migration distances and direction (Chapter 4). The equations for the calculation of resultant wind direction and drift potential are presented in detail in Chapter 6, in conjunction with the sand roses and wind resultants.

## Chapter 4

### DUNE MIGRATION and DUNE VOLUME

#### 4.1 INTRODUCTION

This chapter presents the results of field measurements of dune migration (or displacement) and dune volume. Previous studies, with the exception of Al-Ajmi and Khalaf (1993) examined barchan migration over many years. None have made regular 3D surveys of dune morphology or dune volume over short-term periods (fortnightly or monthly). This chapter presents the results of 3D surveys of barchan and dome dune migration over a short, intense survey period, and dune volume calculations derived through computer analysis. In addition, the relationship between dune migration and size (based on volume) has not been conclusively established, due in part to the difficulty in obtaining accurate volume calculations (Norris, 1965; Lettau, 1969; Long and Sharp, 1964; Petrov, 1976). In this chapter, the relationship between dune migration and size is further examined.

#### 4.2 DUNE MIGRATION

##### 4.2.1 Dune migration at Walvis Bay

Despite the fact that the three Walvis Bay dunes occur within one kilometer of one another, they exhibit distinct variations in migration rates and morphology. Table 4.1 lists the actual movement and the direction of movement for the Walvis Bay dunes between each survey period. Photographs 4.1-4.3 illustrate the morphology of the dunes during early July and at the conclusion of the survey period (end of October). Of the three Walvis Bay dunes, WB3 had the highest total movement (15.75m), compared to WB1 (14.1m), and WB2 (9.75m). This is not surprising, as WB3 is significantly smaller in overall size than either WB1 or WB2.



**Walvis Bay #1 7/7/89**



**Walvis Bay #1 20/10/89**

**Photograph 4.1 Dune morphology, Walvis Bay #1**





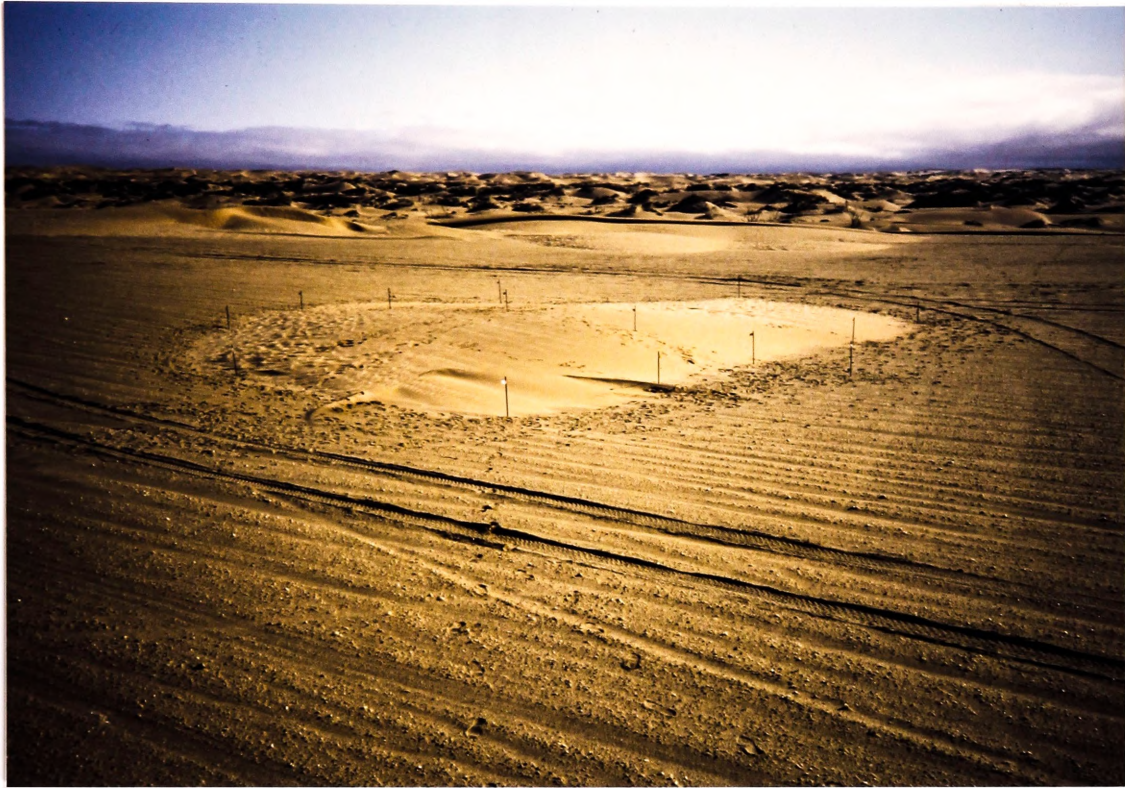
**Walvis Bay #2 8/7/89**



**Walvis Bay #2 20/10/89**

**Photograph 4.2 Dune morphology, Walvis Bay #2**





**Walvis Bay #3 7/7/89**



**Walvis Bay #3 20/10/89**

**Photograph 4.3 Dune morphology, Walvis Bay #3**



## Walvis Bay

Dune	Survey Dates	Dune Ht. (m)	Displacement (m)	Volume (m <sup>3</sup> )
WB1#1	7/7 - 29/7	1.2	4.5	337
WB1#2	29/7 - 11/8	1.3	0.5	439
WB1#3	11/8 - 29/8	1.6	2.6	447
WB1#4	29/8 - 19/9	1.5	2.6	405
WB1#5	19/9 - 8/10	1.4	2.5	395
WB1#6	8/10 - 20/10	1.3	1.6	405
WB1#7		1.5		376
WB2#1	8/7 - 28/7	1.0	3.5	201
WB2#2	28/7 - 11/8	1.1 *	0.6	229
WB2#3	11/8 - 24/8	1.3 *	1.2	341
WB2#4	24/8 - 19/9	0.9	1.8	226
WB2#5	19/9 - 8/10	0.9	2.1	257
WB2#6	8/10 - 20/10	0.9	1.6	226
WB2#7		1.2		198
WB3#1	8/7 - 29/7	0.6 *	4.6	64
WB3#2	29/7 - 12/8	0.6 *	0.4	82
WB3#3	12/8 - 24/8	0.6 *	1.7	83
WB3#4	24/8 - 19/9	0.6 *	3.7	72
WB3#5	19/9 - 8/10	0.5	3.4	49
WB3#6	8/10 - 20/10	0.5	2.0	38
WB3#7		0.5 *		55

Displacement is measured between survey periods.

Dune height represents the highest point of the dune, if a slipface was not present.

\* represents height measurement based on dune height, not slipface height

**Table 4.1 Dune height and displacement**

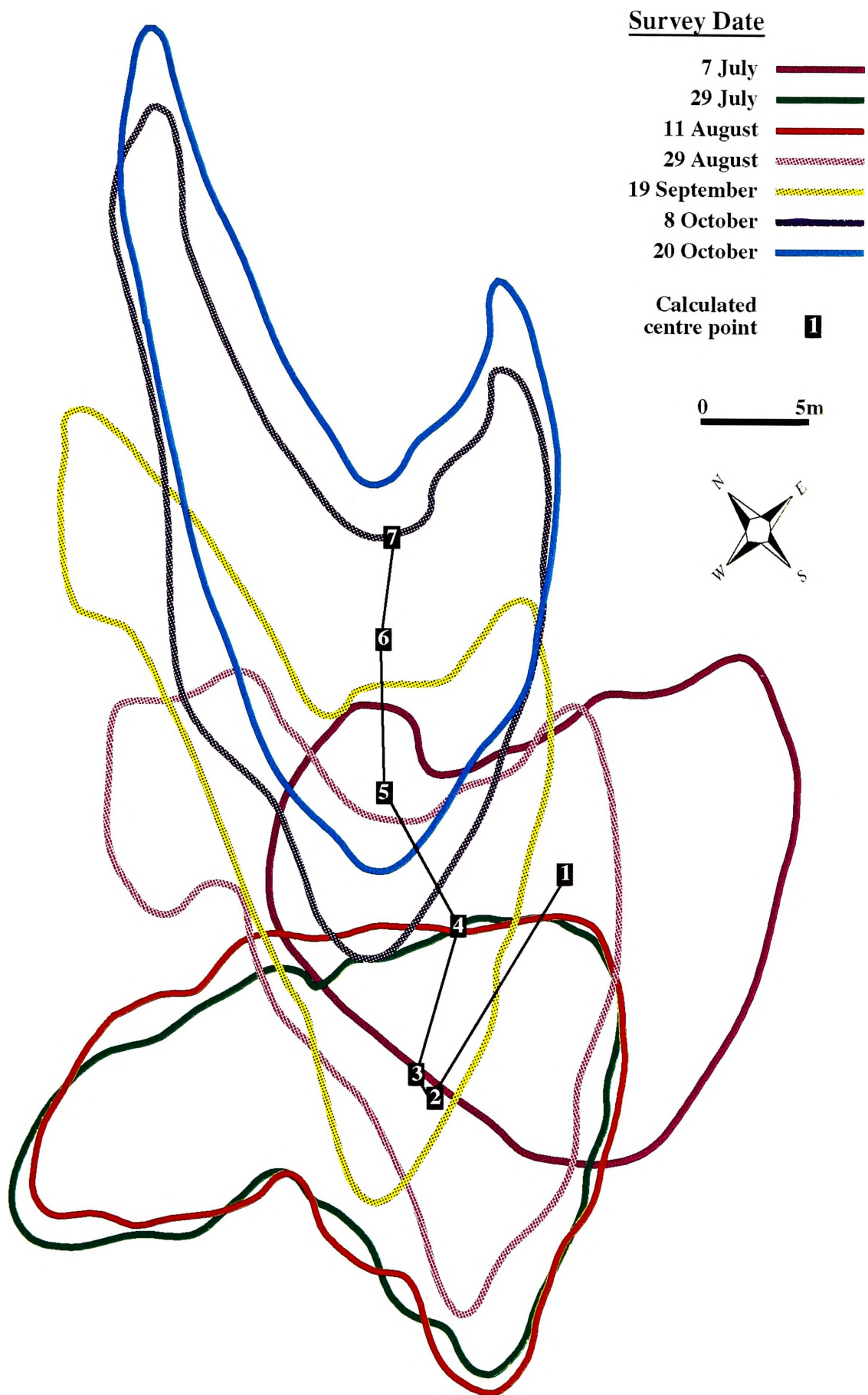
Previous observations of barchan migration by various researchers have indicated that the rate of movement of a barchan is inversely proportional to its mass (Petrov, 1976).

Figure 4.1a-c shows an outline of the dune shape for each survey period as well as the calculated centre point used as a baseline in determining the rate of movement of each dune. The direction of movement is measured by drawing a line from the first dune center point to the second until all are linked. Figure 4.1d shows the resulting line and indication of direction of movement between survey periods.

All dunes migrate in similar patterns, with alignment of the slipface or downwind lee slope being NNE at the commencement of the surveys. The highest amount of movement for all the Walvis Bay dunes was measured between 7 July and 29 July, 1989. Over this period, the direction of movement abruptly shifts to the west for all dunes. On 21 July, 1989, an easterly 'berg' wind occurred, resulting in wind velocities upwards of 60 km/hour. This event accounts for the sudden shift in alignment from northeasterly to westerly.

Another major directional shift occurs at the end of August, between Survey 3 and Survey 4. The dunes align once again in a NNE/NE-direction. WB1 indicates a greater rate of movement, with a corresponding directional change slightly more to the west than either WB2 or WB3. This may be explained by possible upwind variations in topography which may affect downwind flow; this may also explain the distinct elongation of the western horn. WB1 exhibits a reasonably barchanoidal form over the same period, compared to WB2 and WB3, which are distinctly irregular in plan shape. Local variation in flow intensity and direction, and dune height, may explain this morphologic variation, and will be discussed later,.

All dunes continue to migrate in a relatively northeasterly direction from 29 August until the end of the survey period. WB3 continues to advance at a faster rate than both of the other



**Figure 4.1a Outlines of dune shape for Walvis Bay #1**

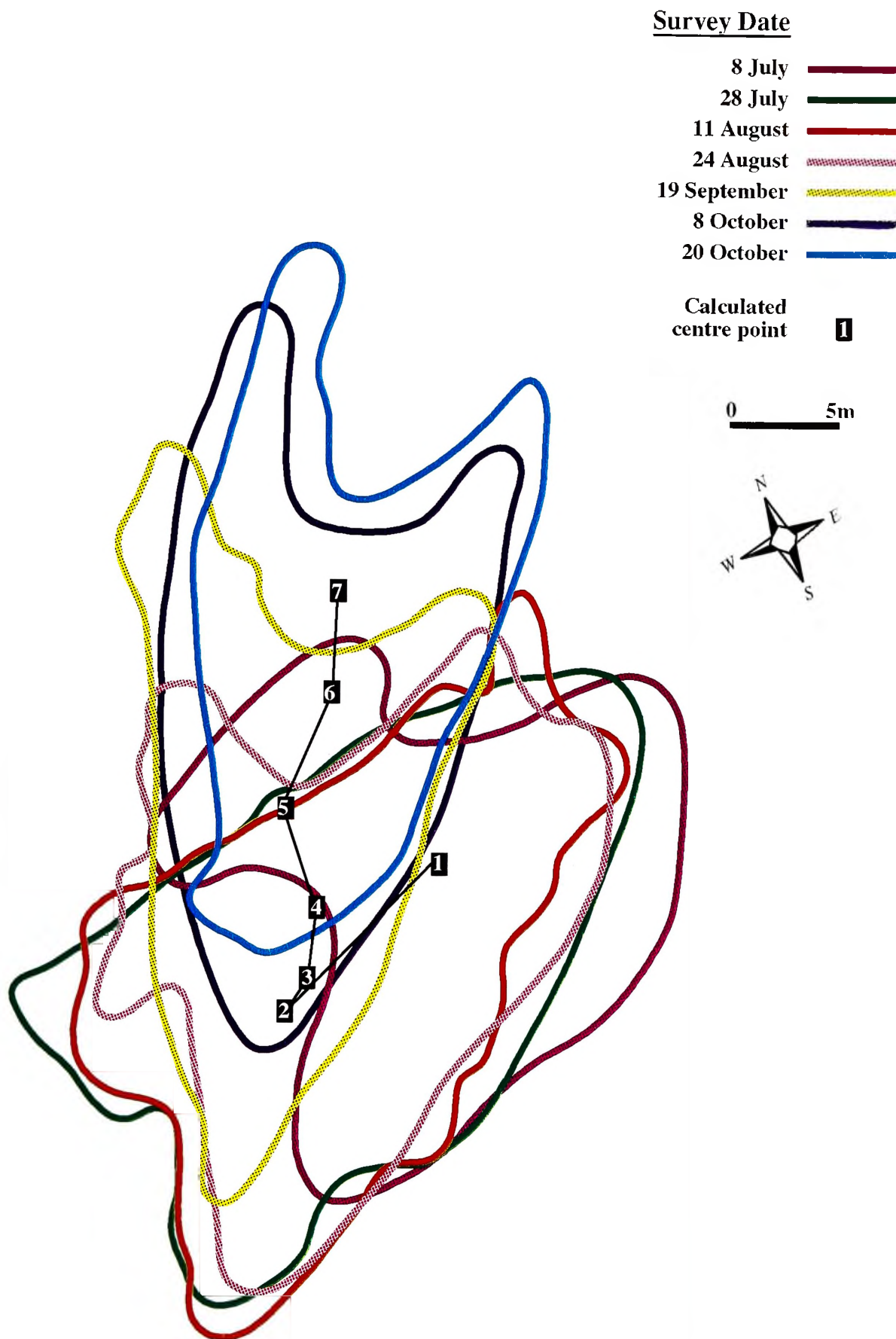


Figure 4.1b Outlines of dune shape for Walvis Bay #2

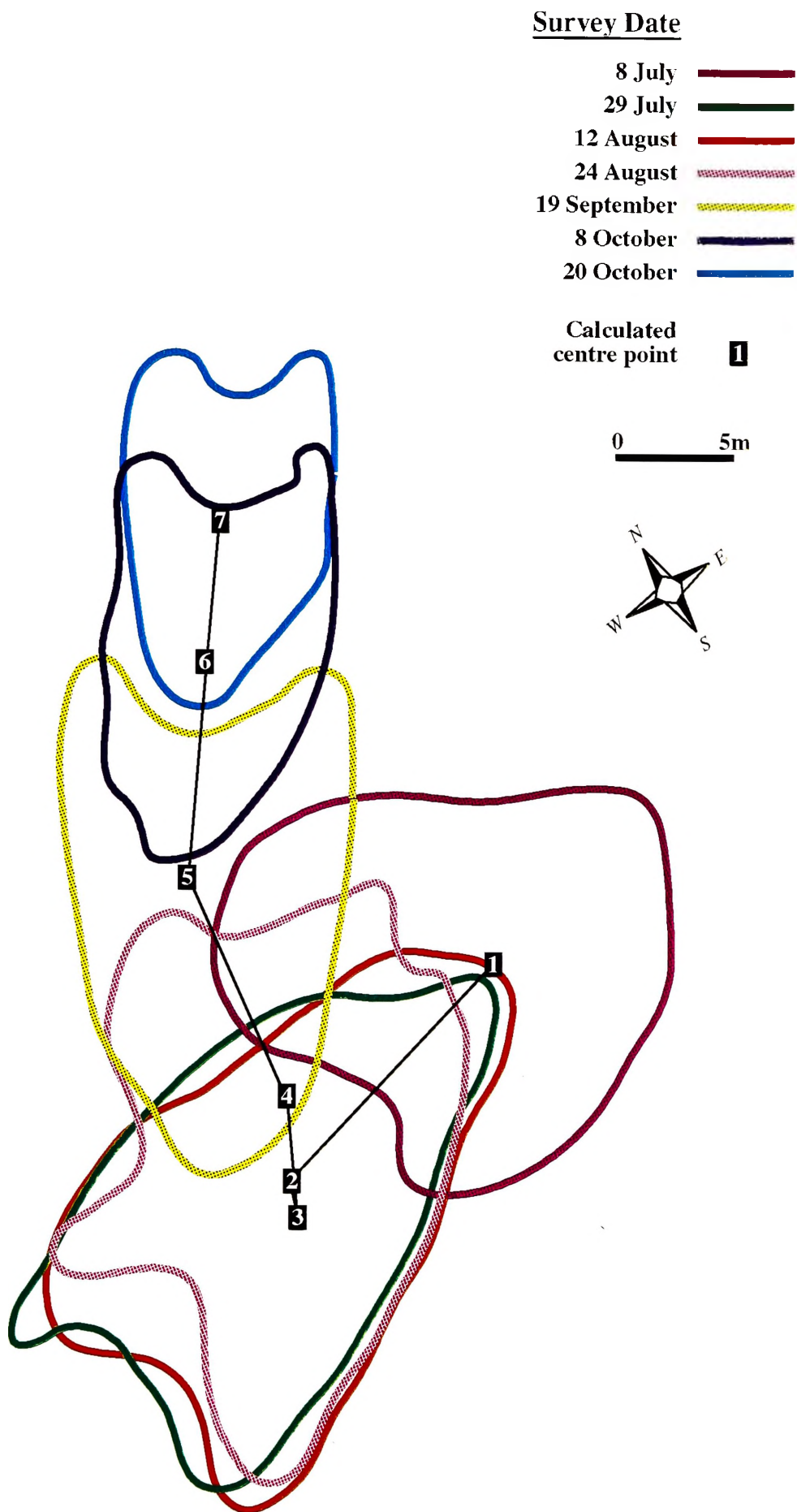
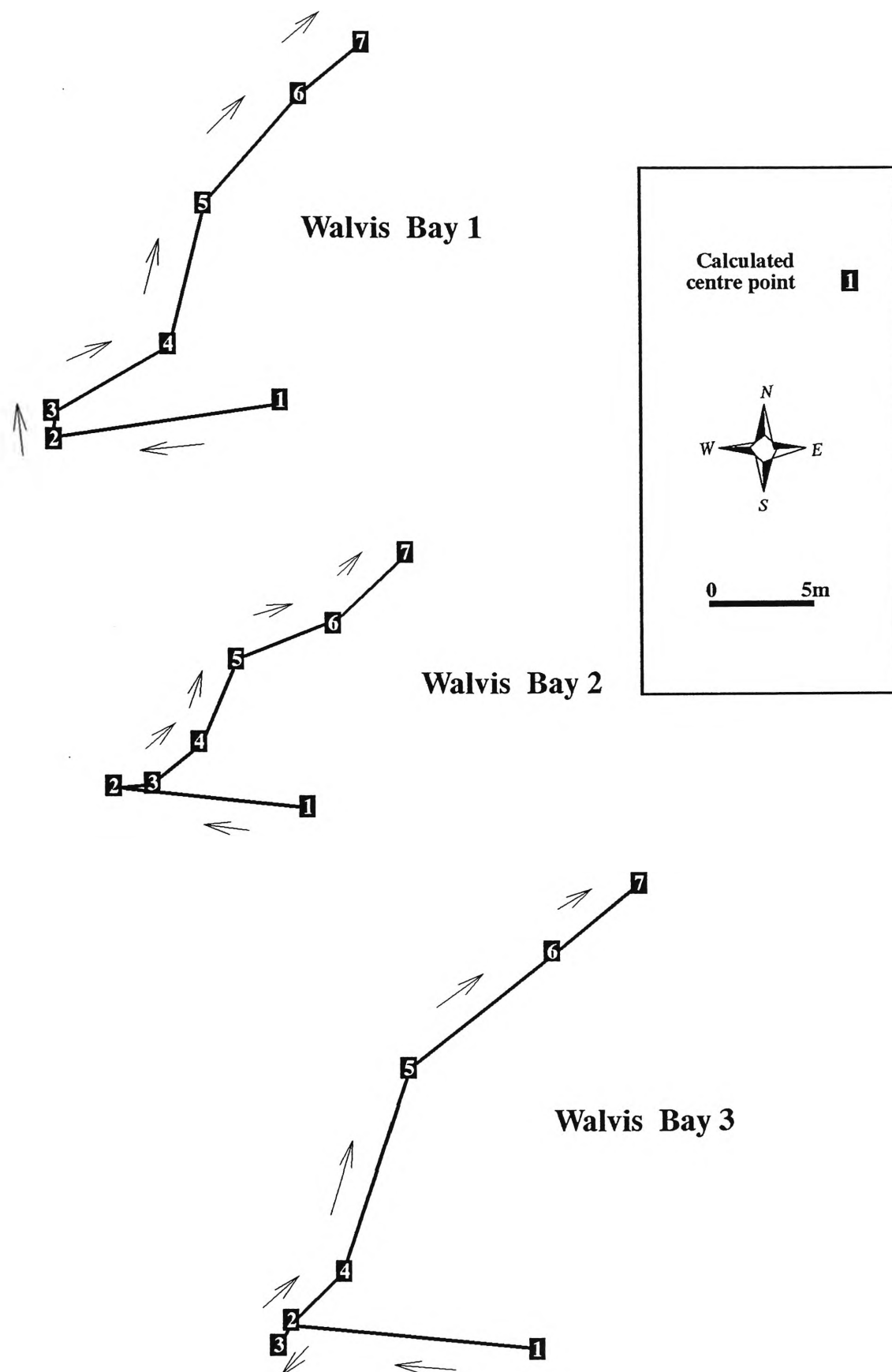


Figure 4.1c Outlines of dune shape for Walvis Bay #3



**Figure 4.1d** Direction of movement of the Walvis Bay dunes

dunes, moving 9.05m from 29 August to 20 October. This represents 57% of WB3 total movement over the entire survey period. WB1 advanced 6.6m over the same period, which represents 47% of total movement. WB2 migrated 5.45m, an amount significantly less than WB3 but still accounting for 56% of total dune movement.

The elongation of the westerly horn of WB1 was first apparent during late August and was probably due to greater exposure to oblique winds, or a change in sand supply. This elongation continues until the conclusion of the surveys, and is barely existent in WB2 and non-existent in WB3, indicating that this asymmetry cannot be entirely explained by the above-mentioned factors, since all the dunes exist within 0.5km of each other and should therefore be subjected to minimal variation in wind regime. This phenomenon was also found by Clos-Arceud (1969, 1971). At the end of the survey period in late October, both WB1 and WB2 exhibit a classic barchan shape, with a well-developed slipface and marked 'horn' development. WB3 exhibited a distinctive barchanoidal morphology during the same period.

#### 4.2.2 Dune migration at Swakopmund

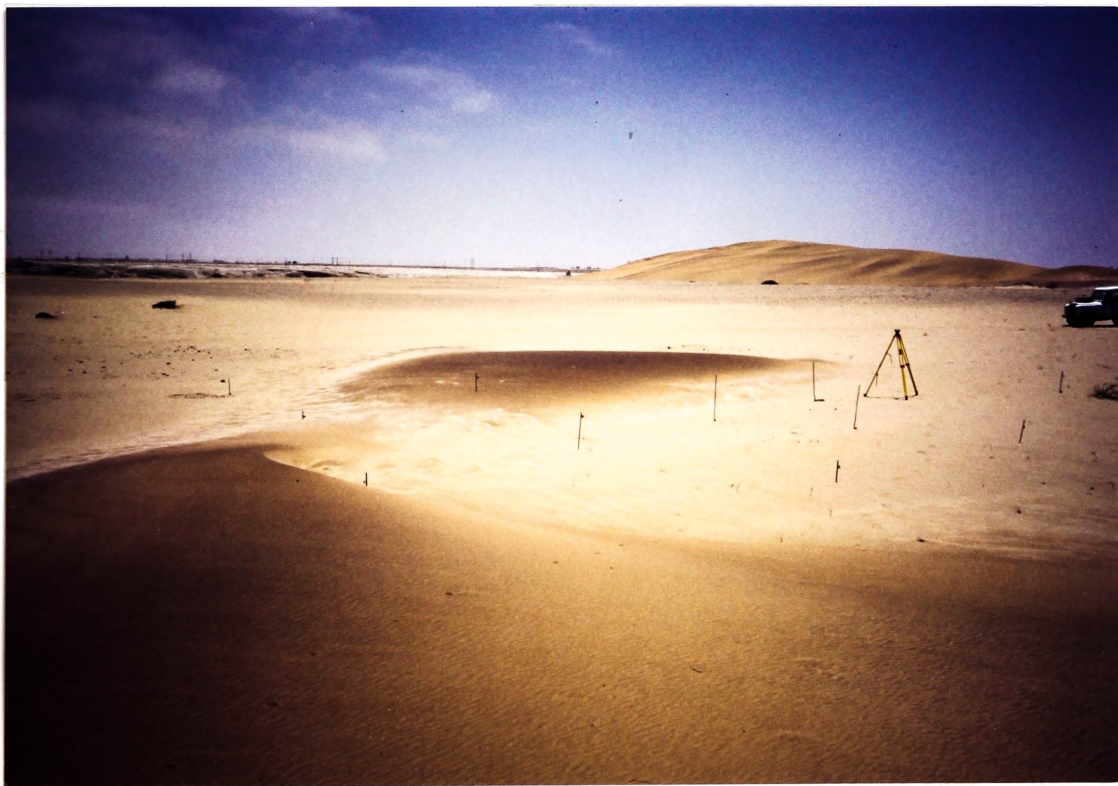
SW2 had the highest total movement (Table 4.2) over the survey period (8.05m) compared to 7.85m for SW1; SW3 had a total displacement of 5.85m but this did not include a measurement of movement between survey 1 and 2. All three dunes exhibit similar migration trends, with most movement for all dunes occurring during mid-July and mid-August. 42% of total measured displacement for SW2 occurred between 9 July and 30 July, compared to 28% for SW1. Dune location presents a plausible reason for this discrepancy, as SW2 was significantly more exposed to the easterly wind than was SW1.

At the commencement of the survey, alignment was to the north or northeast for all dunes (Fig. 4.2a-d). As Photographs 4.4-4.6 indicate, morphology was quite indistinct at this time,





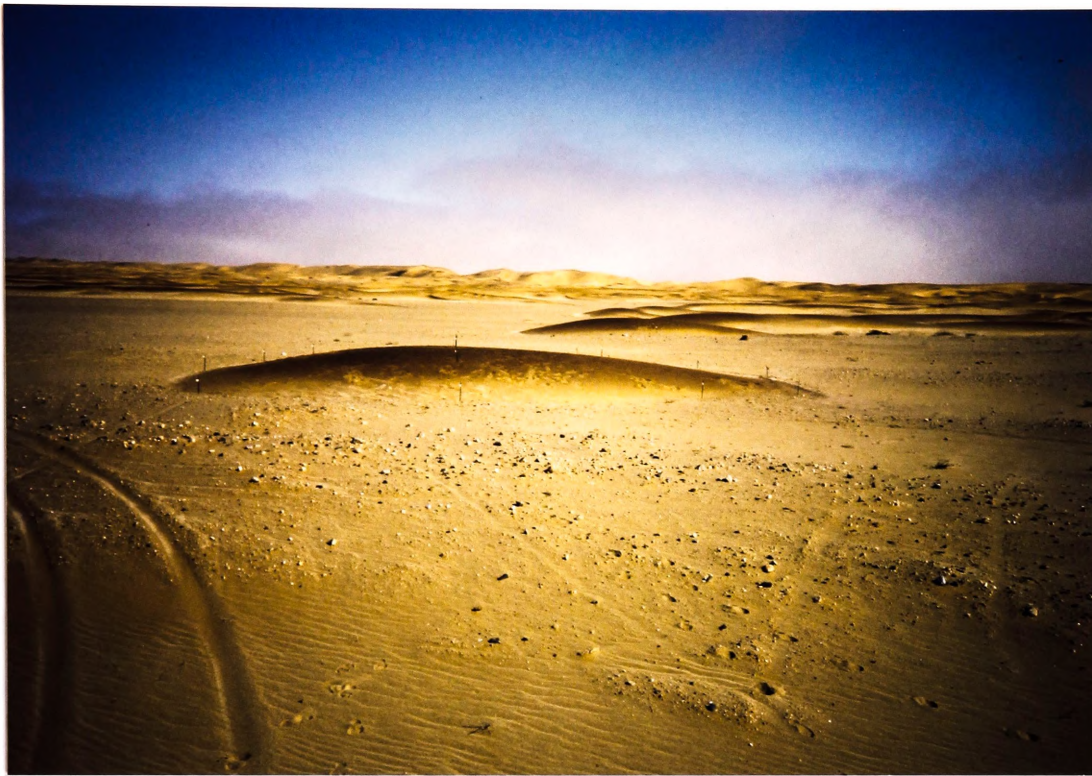
**Swakopmund #1 9/7/89**



**Swakopmund #1 23/10/89**

**Photograph 4.4 Dune morphology, Swakopmund #1**





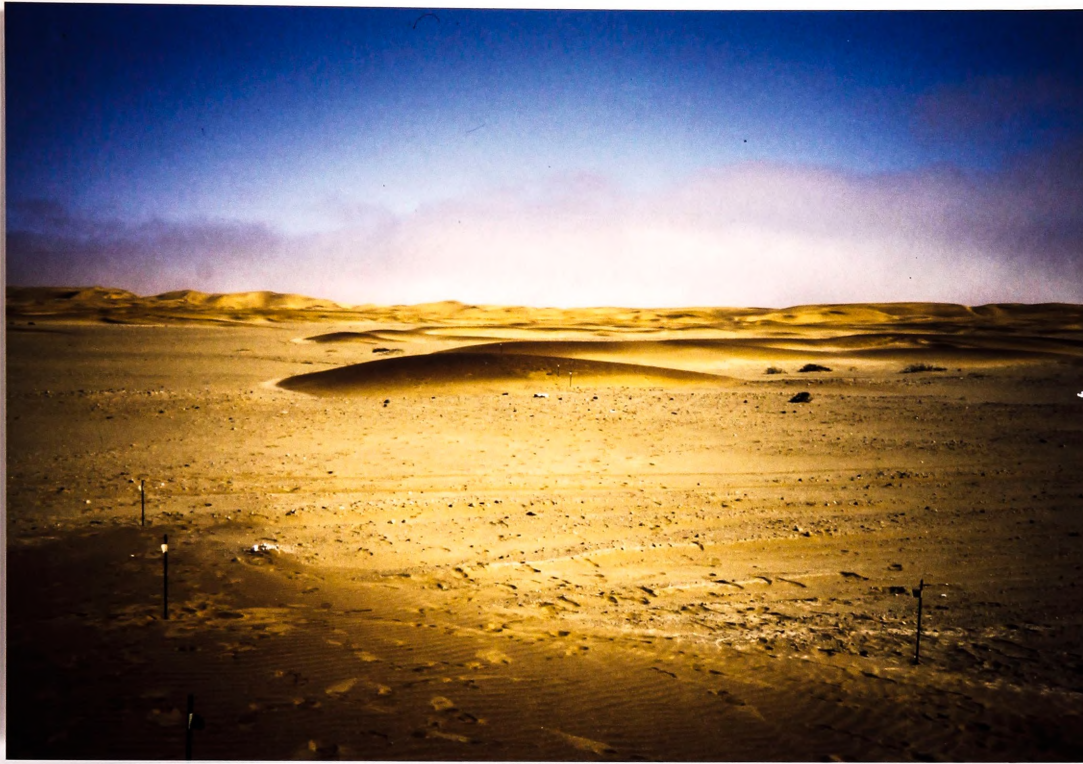
**Swakopmund #2 9/7/89**



**Swakopmund #2 23/10/89**

**Photograph 4.5 Dune morphology, Swakopmund #2**





**Swakopmund #3 30/7/89**



**Swakopmund #3 23/10/89**

**Photograph 4.6 Dune morphology, Swakopmund #3**

## Swakopmund

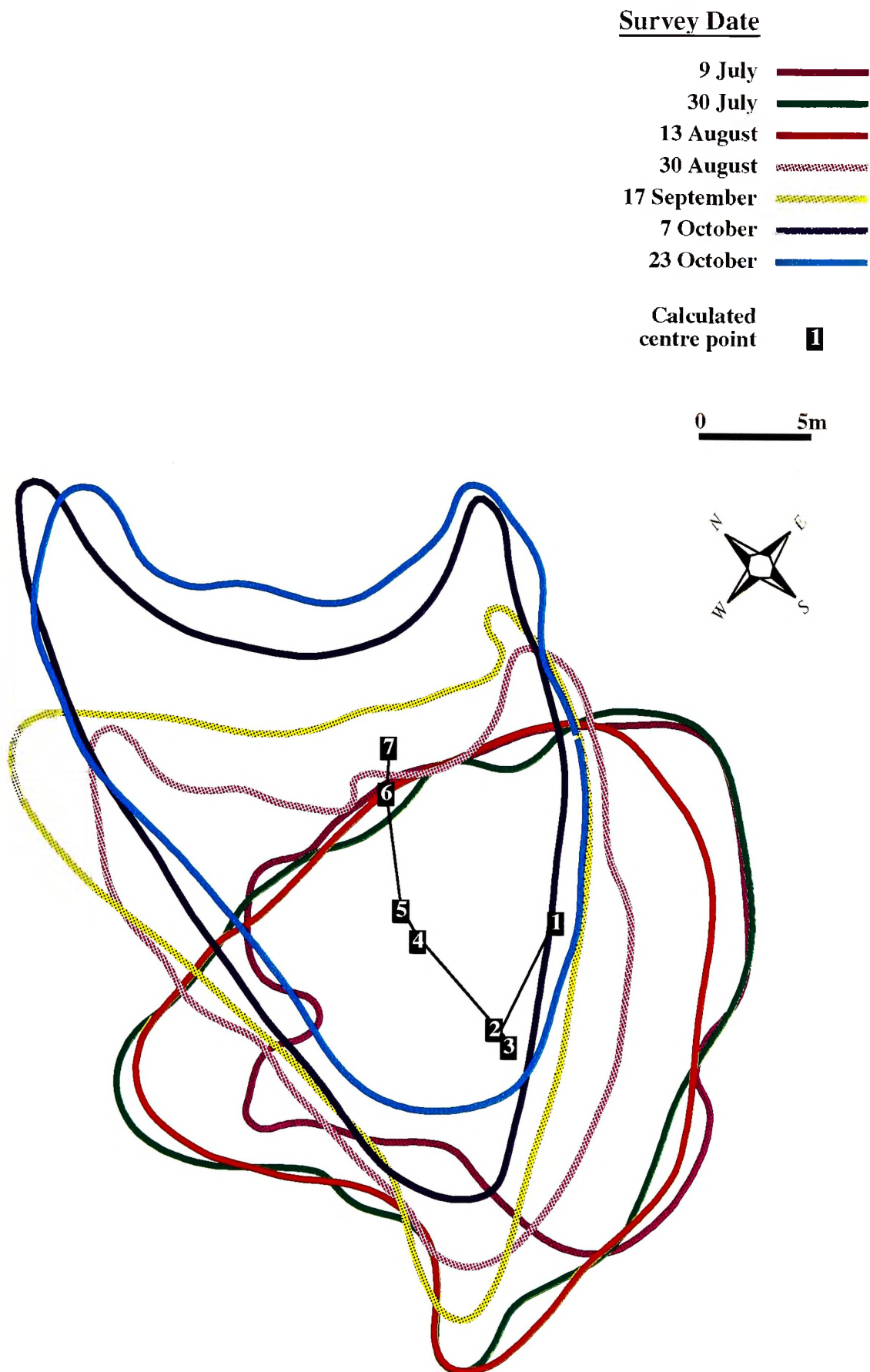
Dune	Survey Dates	Dune Ht. (m)	Displacement (m)	Volume (m <sup>3</sup> )
SW1#1	9/7 - 30/7	1.3 *	2.2	300
SW1#2	30/7 - 13/8	1.4 *	0.25	391
SW1#3	13/8 - 30/8	1.4 *	2.35	416
SW1#4	30/8 - 17/8	0.8	0.5	356
SW1#5	17/9 - 7/10	1.0	1.8	362
SW1#6	7/10 - 23/10	0.3	0.75	315
SW1#7		1.2 *		453
SW2#1	9/7 - 30/7	1.0 *	2.7	160
SW2#2	30/7 - 13/8	0.8	0.6	234
SW2#3	13/8 - 30/8	0.7	2.2	238
SW2#4	30/8 - 17/9	0.7	0.7	204
SW2#5	17/9 - 7/10	0.3	2.0	249
SW2#6	7/10 - 23/10	0.4	1.1	250
SW2#7		0.3		195
SW3#2	9/7 - 30/7	1.0	0.65	336
SW3#3	29/7 - 12/8	0.9	2.1	589
SW3#4	12/8 - 24/8	0.9	0.55	288
SW3#5	24/8 - 19/9	0.6	1.95	291
SW3#6	19/9 - 8/10	0.4	0.6	240
SW3#7		0.5		280

Displacement is measured between survey periods.

Dune height represents the highest point of the dune, if a slipface was not present.

\* represents height measurement based on dune height, not slipface height

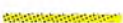


**Table 4.2 Dune height and displacement**




**Figure 4.2a Outlines of dune shape for Swakopmund #1**



Survey Date

9 July   
30 July   
13 August   
30 August   
17 September   
7 October   
23 October 

Calculated  
centre point 

0  5m

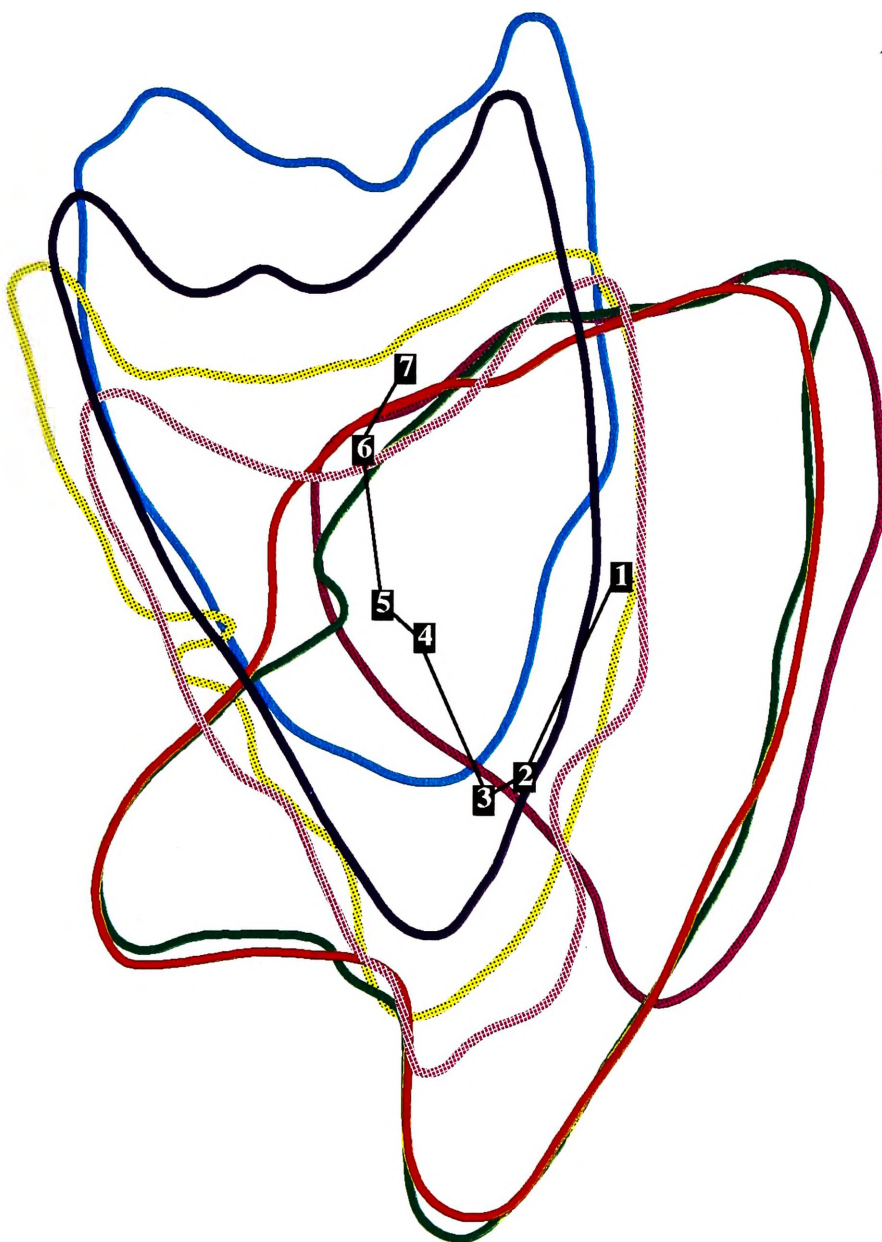


Figure 4.2b Outlines of dune shape for Swakopmund #2

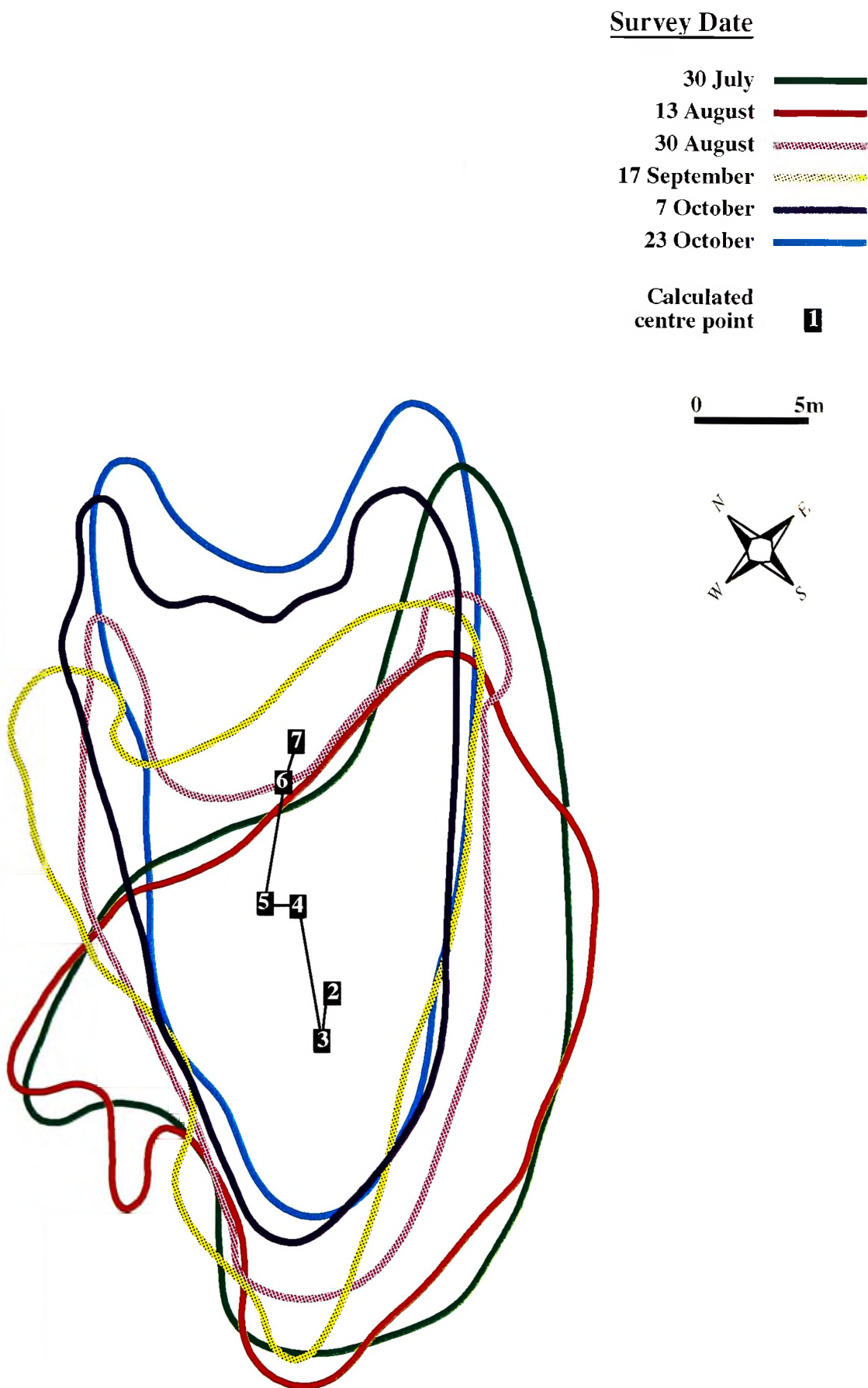


Figure 4.2c Outlines of dune shape for Swakopmund #3

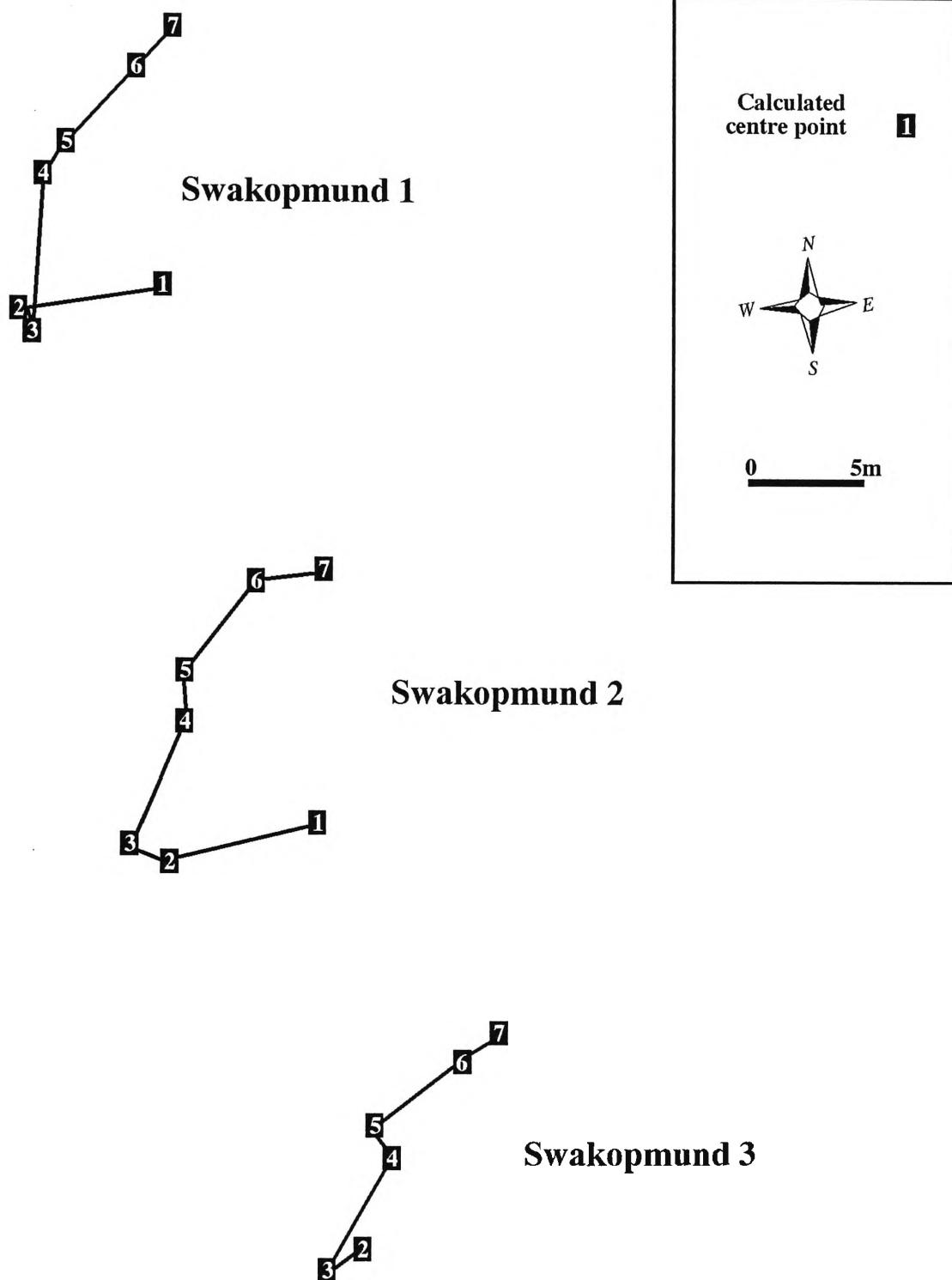


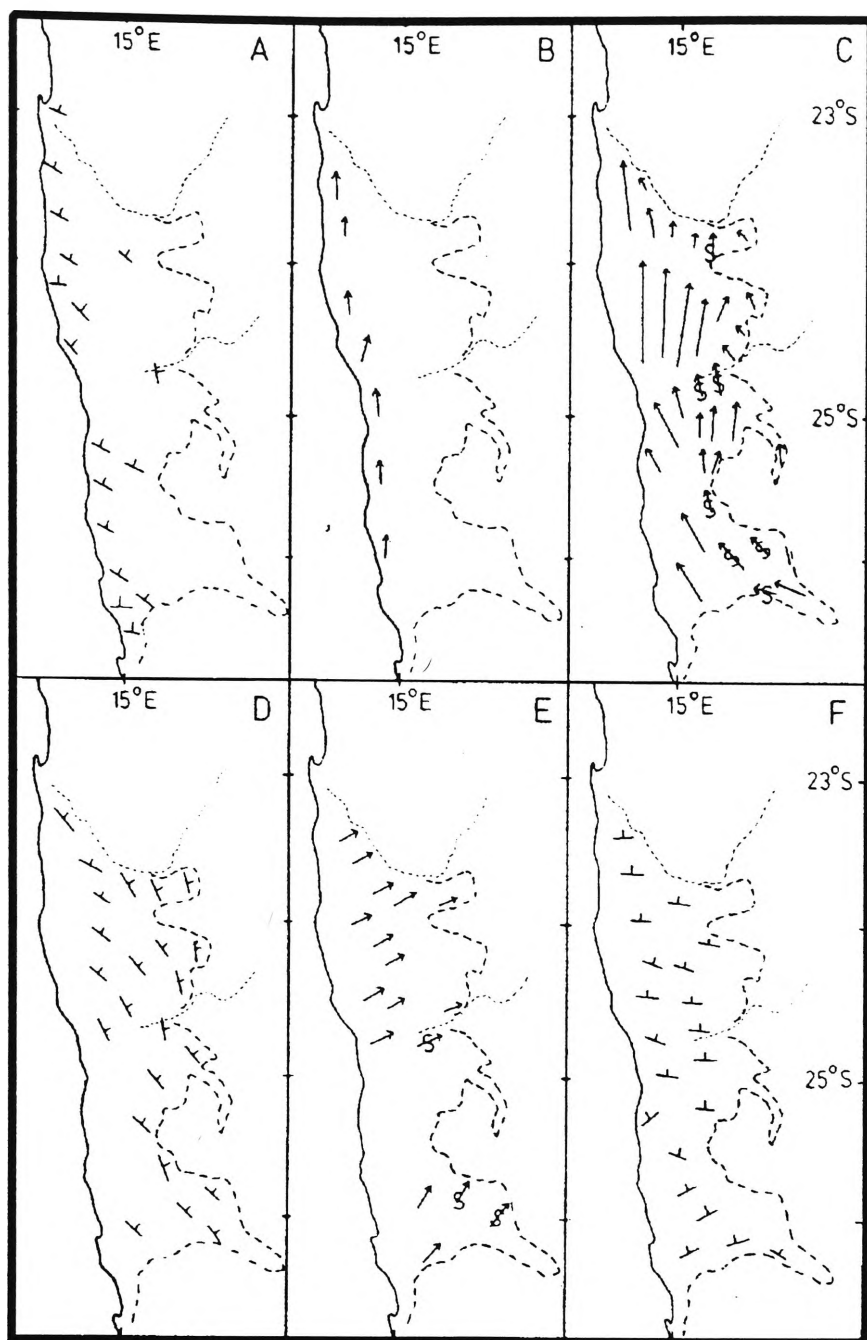
Figure 4.2d Direction of movement of the Swakopmund dunes

making the determination of alignment direction slightly difficult in some cases. A shift to the west occurred during mid- to late July, with another general directional shift to the NNE occurring during mid- to late August. As with the Walvis Bay dunes, the westerly change in migration direction resulted from the easterly storm winds of 21 July. By the end of the survey period, all dunes showed a consistent alignment towards the NNE, the dominant alignment for barchans in the region (Fig. 4.3)(Lancaster, 1989). At this time, SW2 was beginning to develop a slight elongation of the 'western' horn, again a possible result of oblique winds and/or other factors (see Chapter 7 for further discussion).

The Swakopmund dunes migrated at a distinctly slower rate than the Walvis Bay dunes (Table 4.2). The fastest moving dune in the Swakopmund area (SW1) migrated 59% of the distance of the fastest moving Walvis Bay dune (WB3). Since the dunefields are located approximately 40km apart, local variations in wind velocity may explain the discrepancies in movement. Lancaster (1989) indicates that magnitude and direction of sand transport in the Namib can vary widely, even within this small distance (Fig. 4.4). In addition, the Swakopmund dunes are somewhat more protected from the strong southwesterly seabreezes by an extensive transverse dunefield directly upwind of the study area. The Walvis Bay dunes quickly 'recovered' from the easterly storm wind and began to migrate in a northeasterly direction by the end of July, in response to the seasonally predominant southwesterly winds. The Swakopmund dunes did not begin to migrate in this direction until late August.

Another possible explanation for the difference in displacement between Swakopmund and Walvis Bay dunes is the differences in bulk density and grain size and their effect on sand transport. As particle size increases, minimum threshold velocity (or threshold shear velocity) increases. In addition, the minimum threshold velocity increases with particle density (Cooke et al., 1993). The mean grain size of the Swakopmund dunes is 0.21mm, compared to 0.18 for Walvis Bay. Bulk density is also greater; 3.88g/cm<sup>3</sup> for Swakopmund and 2.76g/cm<sup>3</sup> for

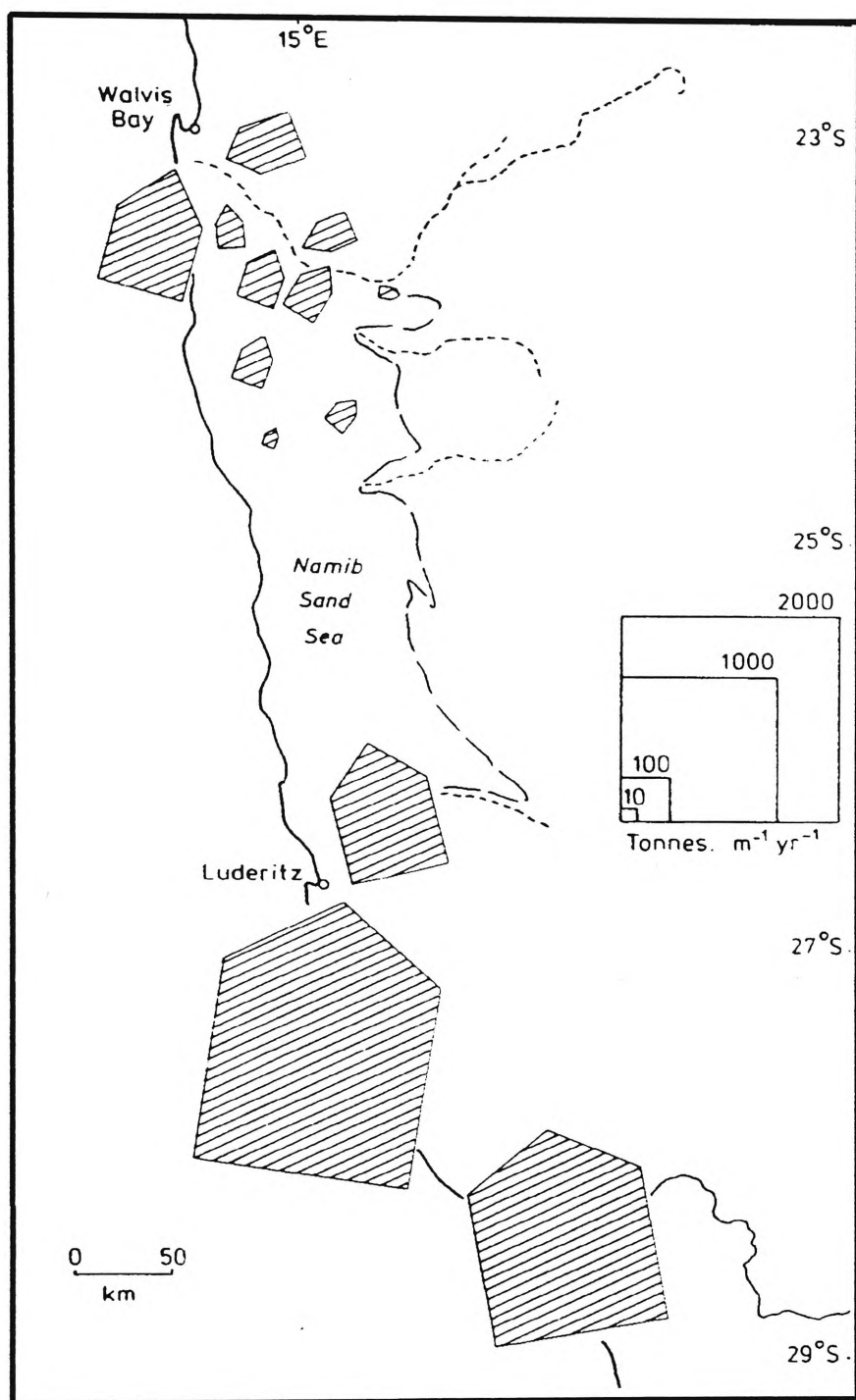




**Pattern of dune alignment in the Namib Sand Sea**  
(from Lancaster, 1989).

- A = Crescentic dunes  
Bar indicates strike of crest; tick, orientation of slipface.
- B = Oblique linear elements in areas of crescentic dunes
- C = Linear dunes and main ridges of star dunes
- D = East flank barchanoid dunes in areas of complex linear and star dunes. Bar indicates strike of crest; tick, slipface orientation
- E = Corridor crossing dunes in areas of linear dunes and subsidiary arms of star dunes
- F = Zibar  
Bar indicates strike of crest; tick, lee slope

**Figure 4.3 Dune alignment in the Namib Sand Sea**



Magnitude and direction of resultant potential sand transport in the Namib Sand Sea (from Lancaster, 1989).

**Figure 4.4** Magnitude and direction of sand transport in the Namib Sand Sea

Walvis Bay. This greater particle size and bulk density would require a higher minimum threshold velocity to entrain sediment at Swakopmund.

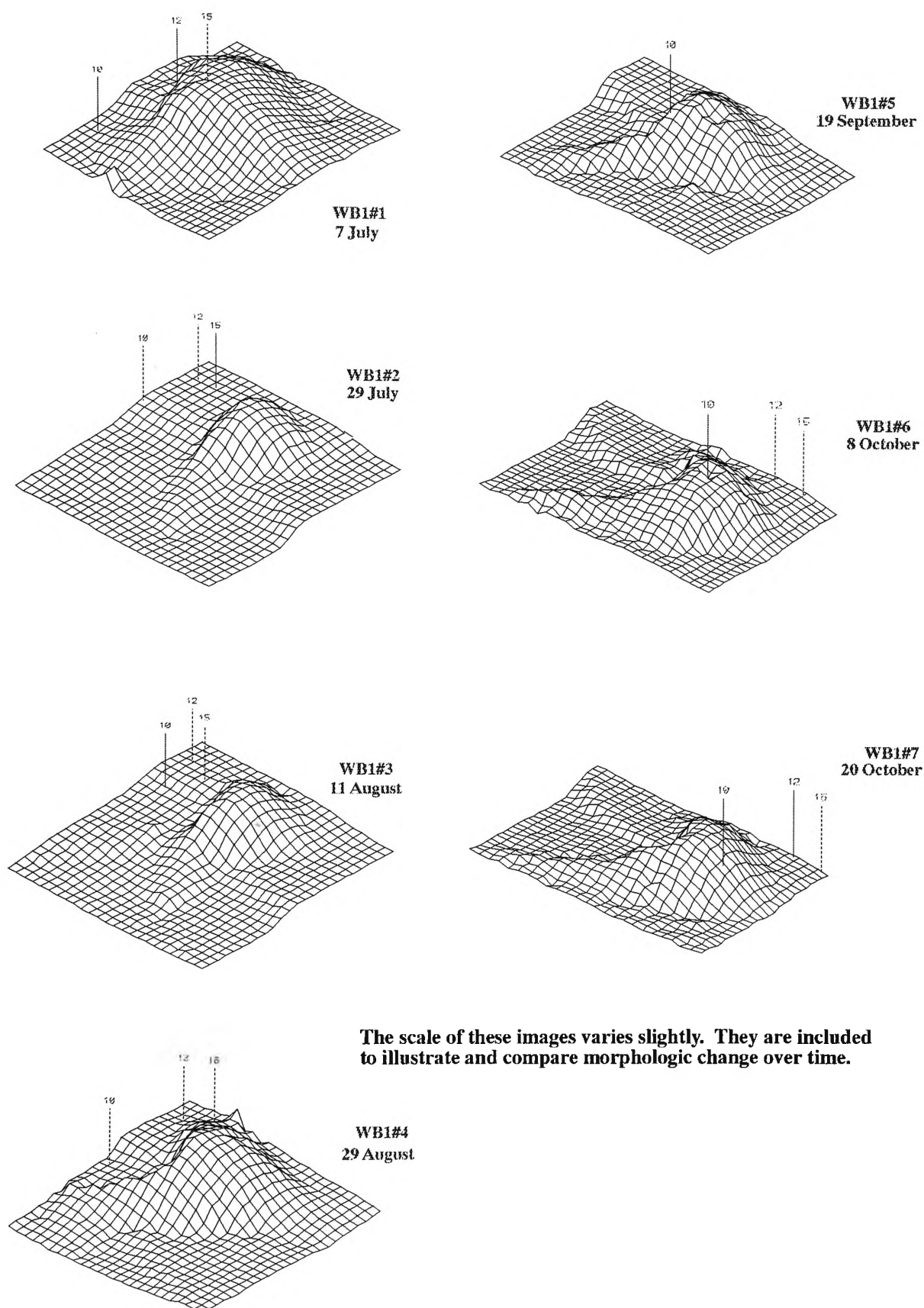
### 4.3 DUNE PLAN SHAPE AND MORPHOLOGY

At the onset of the survey, all Walvis Bay dunes were of an indistinct morphology. However, throughout most of the survey period, the dunes could be defined as either barchans or barchandoidal in form. Figure 4.5a-f

illustrates the 3D images of the Swakopmund and Walvis Bay dunes, illustrating the morphologic change of each over time. These diagrams are not to scale, and are included only to show the variation in form.

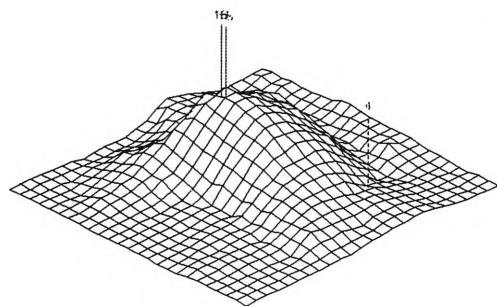
The dunes of Swakopmund have been generally termed 'dome dunes' (Ward, pers. comm.). Morphologically, they do not conform to the classic dome shape defined and recognized by a variety of researchers (see Chapter 2). They often contain slipfaces and are irregular in shape. During the month of October, all the dunes were beginning to show distinct 'horn' development, inconsistent with the accepted definition of a dome. Over most of the survey period, dune morphology was unable to be clearly defined by the accepted criteria.

For both the Walvis Bay and Swakopmund dunes, there appears to be a 'transitional' form observed in all dunes subsequent to an abrupt shift in the wind regime. The lag time between changes in wind direction and dune adjustment to this change results in a dune of indistinct morphology, or this 'transitional' form. Readjustment to a change in conditions takes time, known as 'relaxation time', during which the dune morphology is not in full equilibrium with the current wind direction.

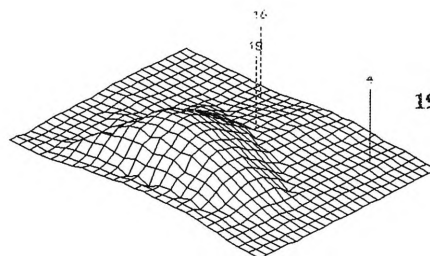


**Figure 4.5a 3D images of Walvis Bay #1**

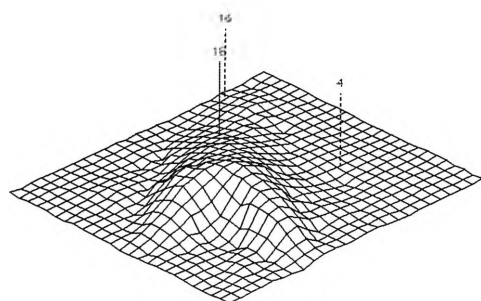
**WB2#1**  
8 July



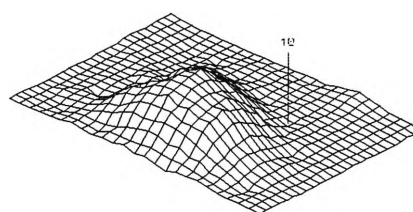
**WB2#5**  
19 September



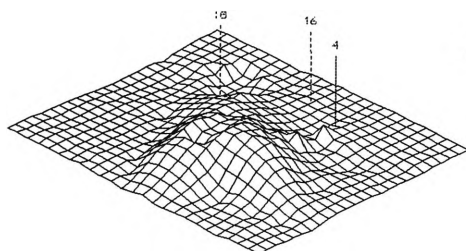
**WB2#2**  
28 July



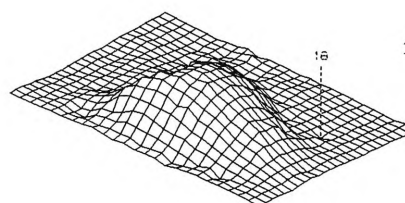
**WB2#6**  
8 October



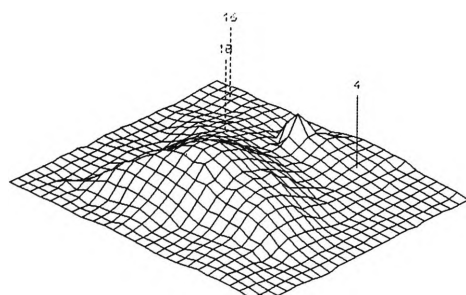
**WB2#3**  
11 August



**WB2#7**  
20 October

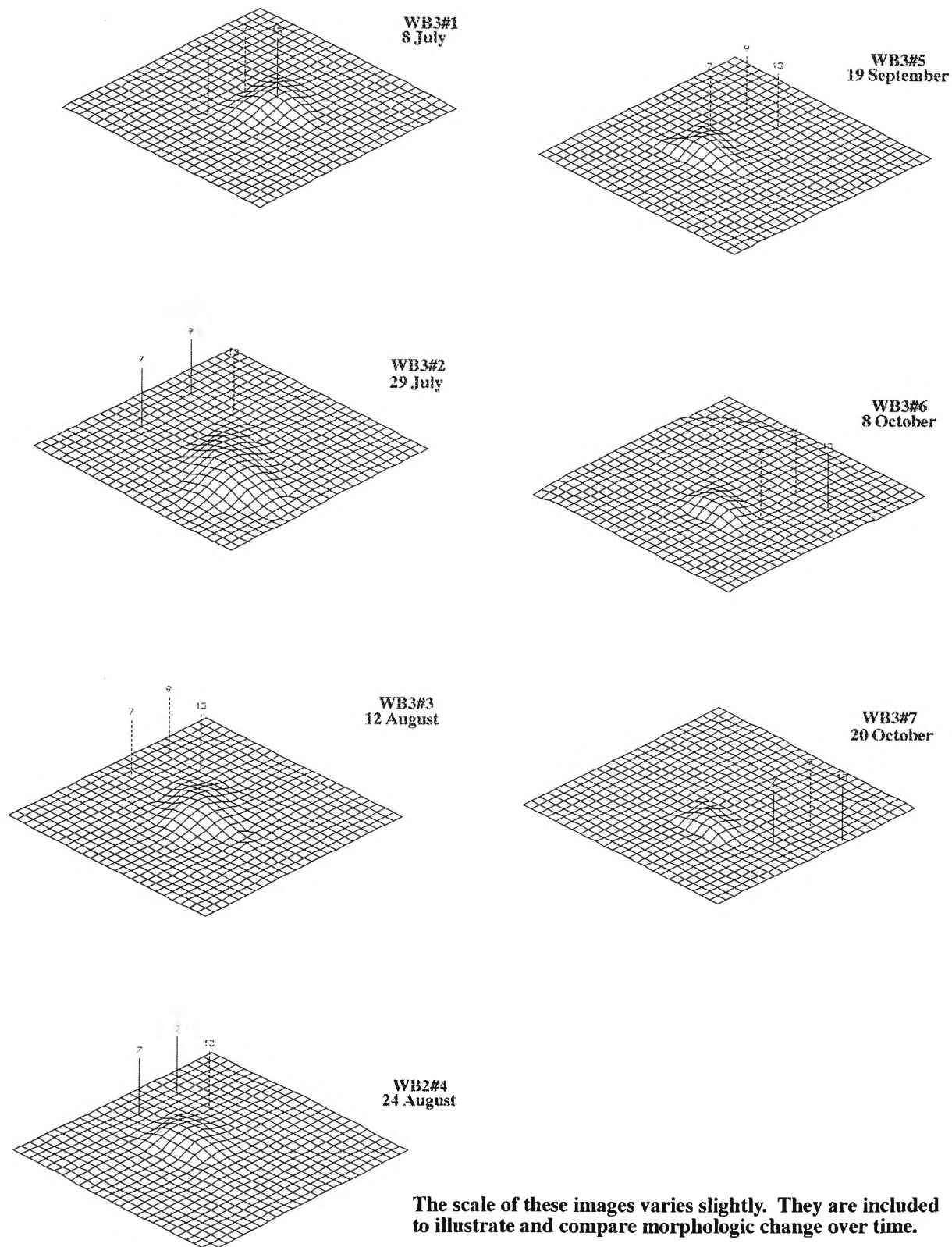


**WB2#4**  
24 August

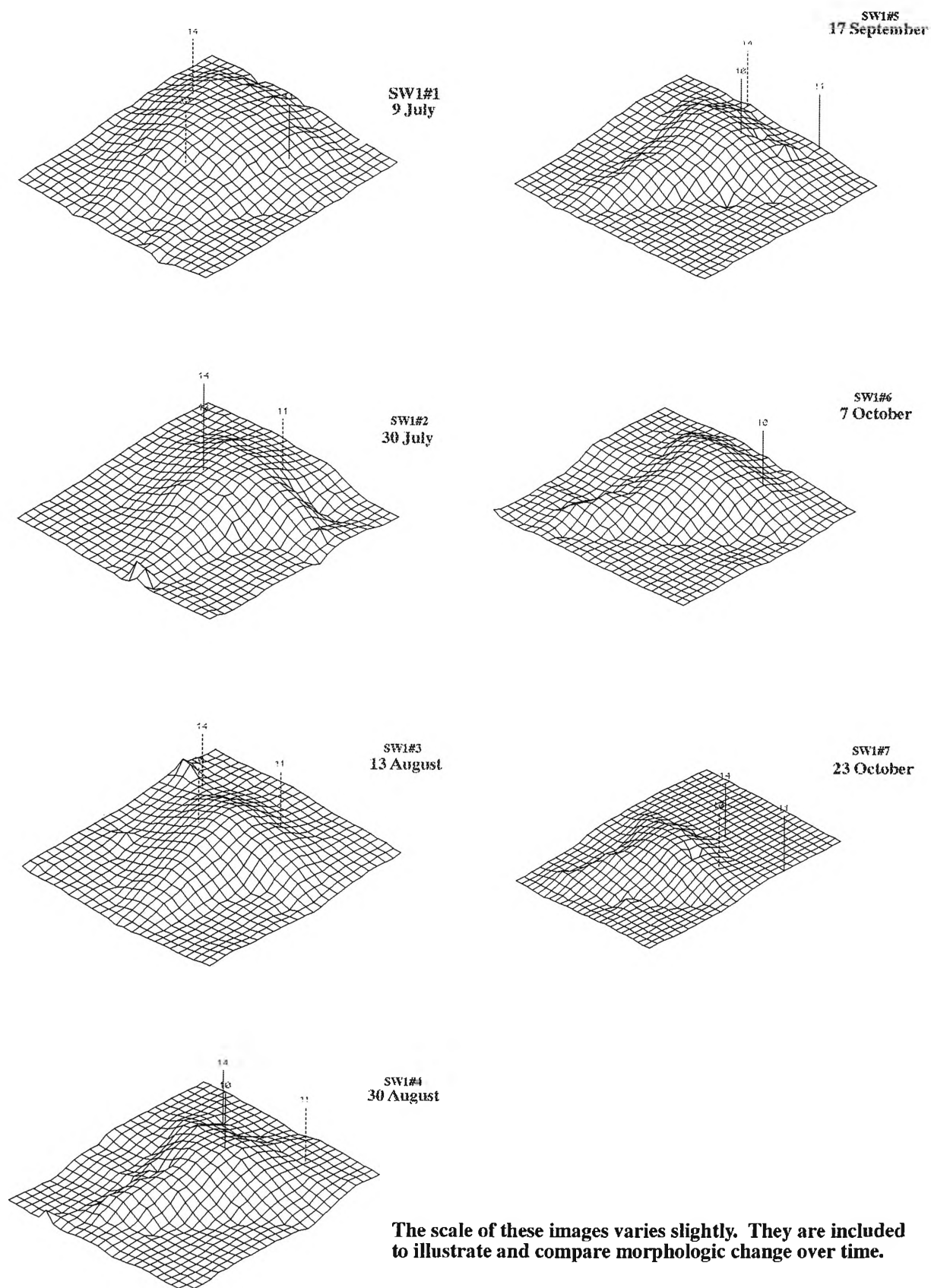


The scale of these images varies slightly. They are included to illustrate and compare morphologic change over time.

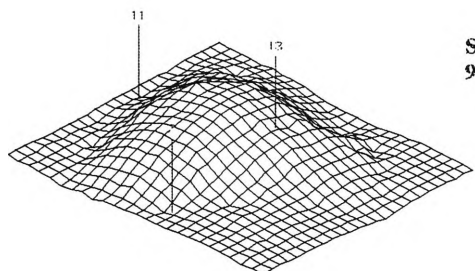
**Figure 4.5b 3D images of Walvis Bay #2**



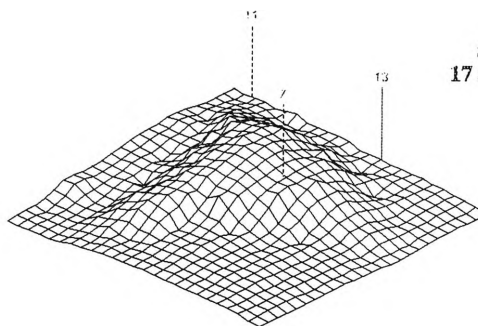
**Figure 4.5c 3D images of Walvis Bay #3**



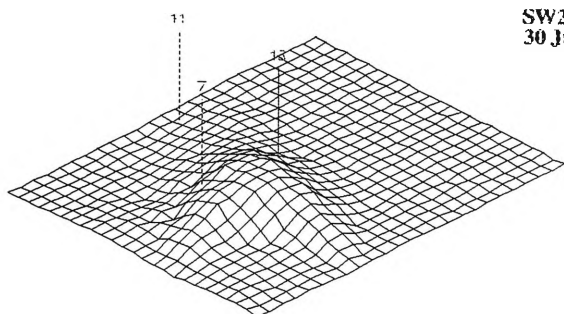
**Figure 4.5d 3D images of Swakopmund #1**



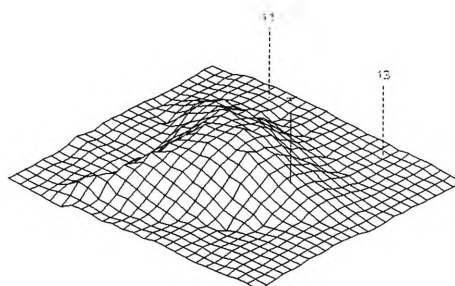
SW2#1  
9 July



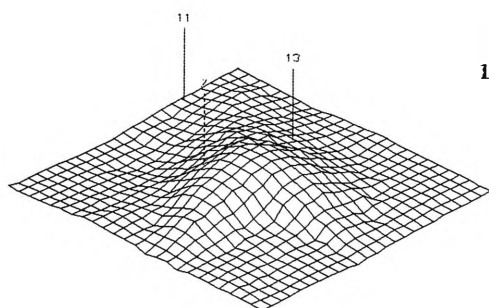
SW2#5  
17 September



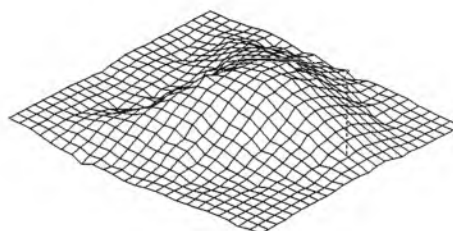
SW2#2  
30 July



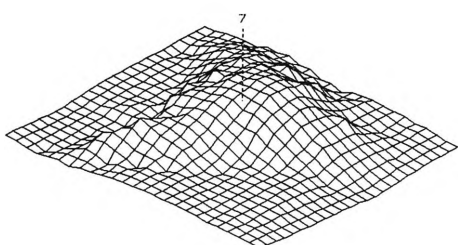
SW2#6  
7 October



SW2#3  
13 August



SW2#7  
23 October

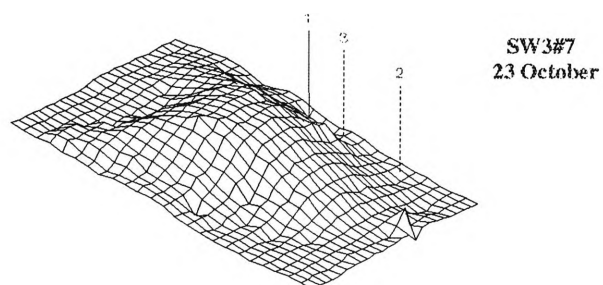
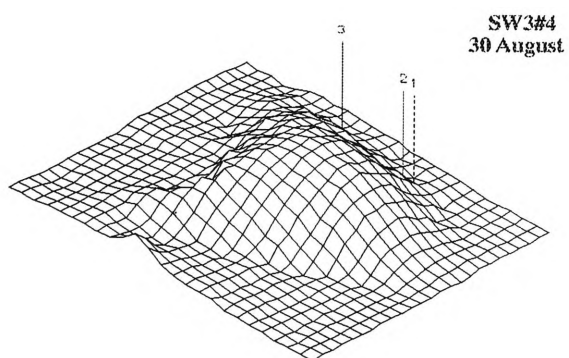
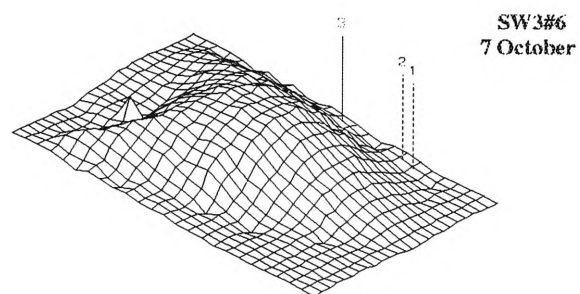
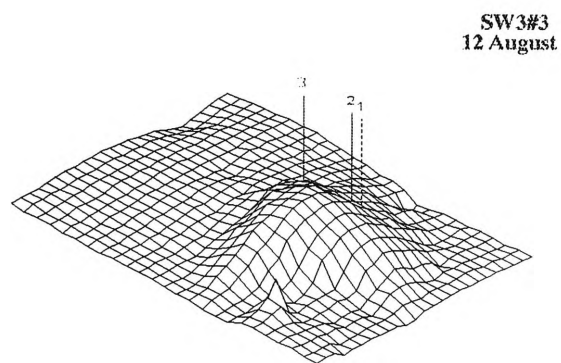
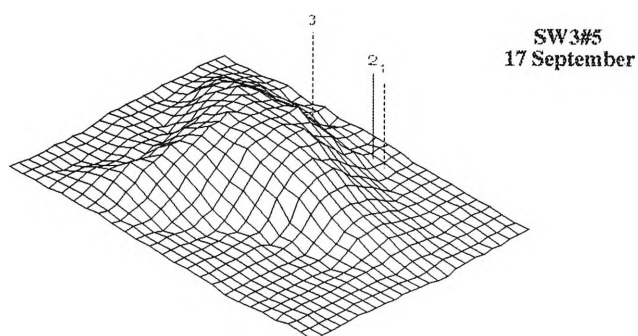
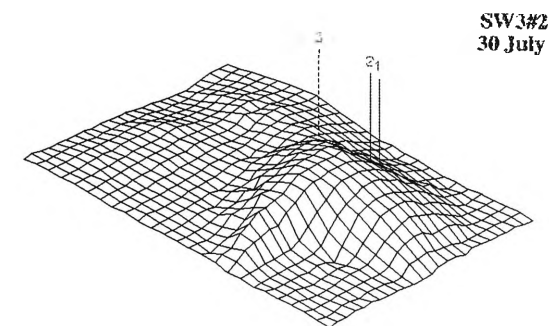


SW2#4  
30 August

The scale of these images varies slightly. They are included to illustrate and compare morphologic change over time.

**Figure 4.5e 3D images of Swakopmund #2**





The scale of these images varies slightly. They are included to illustrate and compare morphologic change over time.

**Figure 4.5f 3D images of Swakopmund #3**

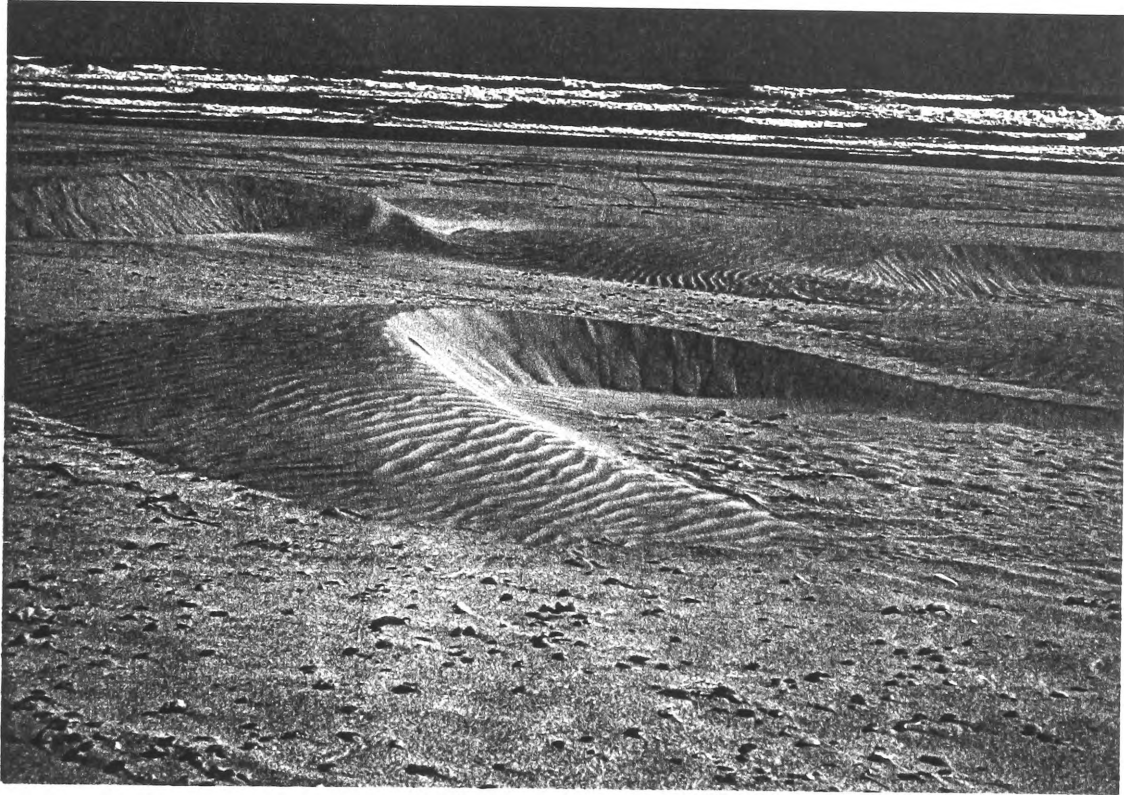
Equilibrium, as defined by Collins Dictionary (1986), is "any unchanging state of a body, system, etc. resulting from the balance of the influences to which it is subjected". By this definition, a sand dune is unable to achieve a state of equilibrium, due to the constantly changing nature of wind flow and sand transport, and their effect on the dune shape. An equilibrium shape has been defined by Yalin (1977, in Cooke et al., 1993) as "one that produced the smoothest flow and thus equalized energy loss in the streamwise direction" (p. 327). Hastenrath (1967) asserts that "under uniform wind conditions, with only moderate sand supply and with a flat underlying surface, barchans may move largely under conservation of their size and shape. Such a 'steady-state' barchan may be considered as an aerodynamic equilibrium form" (p. 329). If the wind velocity and direction remain constant over a reasonable period of time, the dune will adjust to this change and ultimately attain a shape in 'equilibrium' with the conditions. Howard et al. (1977, 1978) indicate that a barchan can maintain an equilibrium shape as a result of sand transport and flow divergence up the curved windward slope towards the wings, implying feedback between length, curvature, windward slope angle, and incoming rate of sand transport and slipface height.

Winds that persist long enough to establish equilibrium forms are rare according to Cooke et al. (1993), an opinion shared by Petrov (1976) who observed that the wind flow around the whole configuration give it a certain stability in motion, and enabled it to maintain its configuration under normal conditions. However, barchans are not stable relief forms. The most appropriate way to describe the barchan form is one which exists in a perpetual state of 'dynamic equilibrium', constantly adjusting to variations in wind regime and sand transport. In addition, should sand supply remain constant, a barchan can still exhibit inconsistencies in displacement depending on whether the barchan is growing or in a steady-state condition, either of which can be determined through morphological analysis (Long and Sharp, 1964). Therefore, although a barchan is strongly affected by changes in sand supply and wind regime, should these two parameters remain constant over time, displacement may vary, depending on

whether the barchan is 'growing' or 'shrinking', or in a steady-state condition, irregardless of differences in height (Bagnold, 1941).

Lettau and Lettau (1969), and Hastenrath (1967) observed that irregularities in shape were limited to smaller dunes, and that only larger dunes attained the 'ideal' crescentic shape. Hastenrath analyzed dunes of varying heights. For a dune with a height of 0.6m, comparable in a few instances to Swakopmund and Walvis Bay dunes, the shape was barchanoidal, exhibiting less than ideal symmetry or slipface development. A dune of 2.6m in height provided an example of a barchan with regular symmetry and a well-developed slipface (Hastenrath, 1967). Of the Walvis Bay/Swakopmund dunes, only WB1 and, to a lesser extent, WB2, towards the end of the survey period, actually present good examples of full barchan morphology. These dunes are between 0.9m and 1.5m in height. Another example of small dunes which exhibit classic barchan form were obtained from observations made at Cactus Beach, South Australia (Hesp and Hastings, unpub. field work, 1989). These dunes were less than 0.5m in height; interestingly, they, too, exhibited classic barchan morphology (Photograph 4.7). It appears that at some point between 0.5m and 0.9m height, without taking into consideration other influences such as sand transport or wind controls, the dune shape will change from barchanoidal to full barchan in a unidirectional wind field. However, this conclusion is not consistent for all dunes, given the data from Cactus Beach.

In contrast to barchans, dome dunes, as Allen (1982) acknowledges, represent a form which is relatively stable and aerodynamic. As such, little field research has been conducted on the aerodynamic controls of their morphology. A detailed discussion on the aerodynamic properties of the Namib dunes is included in Chapter 7.



**Photograph 4.7 Barchan from Cactus Beach, South Australia exhibiting classic barchan morphology.**

#### 4.4. SUMMARY OF DUNE MIGRATION

Should wind and sand transport conditions remain constant for a minimum amount of time, a classic barchan shape will be attained, and maintained during migration, implying that at a certain point an 'equilibrium' morphology is possible. Prior to adjustment to changes in wind conditions, obvious 'transitional forms' are recognized, which do not fall into the recognized categories of dune types, based on the accepted classification criteria. A detailed discussion of these 'transitional' forms will be included in Chapter Six.

Hastenrath (1967), observed that the classic barchan shape is observed only in larger dunes, i.e. greater than 0.6m in height. It follows, therefore, that only larger dunes are able to attain this equilibrium morphology, a conclusion that is disputable based on this study. An equilibrium shape is achievable, provided it is specified as 'dynamic' equilibrium; it is not limited to larger dunes, particularly if 'larger' is determined by slipface height. The Walvis Bay dunes, with the exception of WB3, are 'larger' than the Swakopmund dunes, based on their slipface heights. However, displacement measurements indicate that Walvis Bay dunes moved significantly more than did the Swakopmund dunes, implying that other controls are affecting dune movement. These controls are primarily wind speed and direction, and dune volume. Long and Sharp (1964) recognized this and suggested that volume changes within a dune should affect its rate of movement.

The following sections presents volume calculations for both study areas and the relationship between 'size', based on these results, and displacement rates. A holistic discussion on displacement, height, and volume is presented in Chapter Six, where the analysis of wind fields is also presented.

## 4.5 DUNE VOLUME

Research on the relationship between volume and displacement has been relatively limited, due in part to the difficulty in determining the volume of barchans in the field (Petrov, 1976). This difficulty is attributed to the fact that "a barchan dune is an irregular solid bounded by curved surfaces; therefore, any practical means for determining its volume can give only an approximate value" (Norris, 1965, p. 301). With the level of error involved in the calculation of volume, any resulting conclusions derived from these traditional calculation methods are potentially suspect.

In the following section, the results of the computer-generated volume calculations for the Namib dunes are presented. The relationship between volume and displacement, or migration, is also discussed, with specific reference to both the Walvis Bay/ Swakopmund study areas and previous barchan/dome studies. Further discussion on the relationship between volume, displacement, and calculated sand transport directions can be found in Chapters 5 and 6.

### 4.5.1 Dune volume at Walvis Bay

Volume calculations for the Walvis Bay dunes indicate that volume fluctuations follow similar trends throughout the survey period (Fig. 4.6). Directly following the initial survey, a marked increase in volume occurred at the end of July, particularly noticeable for WB1. This increase is possibly related to the easterly storm wind of 21 July, which resulted in a significant increase in sand transport across the exposed gravel plain to the east. The Walvis Bay dunes were exposed at the downwind end of this plain and probably received an input of sediment.

Dune volume gradually decreases over the remainder of the survey period. Overall, WB1 recorded a 10% net increase in dune volume, while WB3 showed a 13% decrease. WB2 also

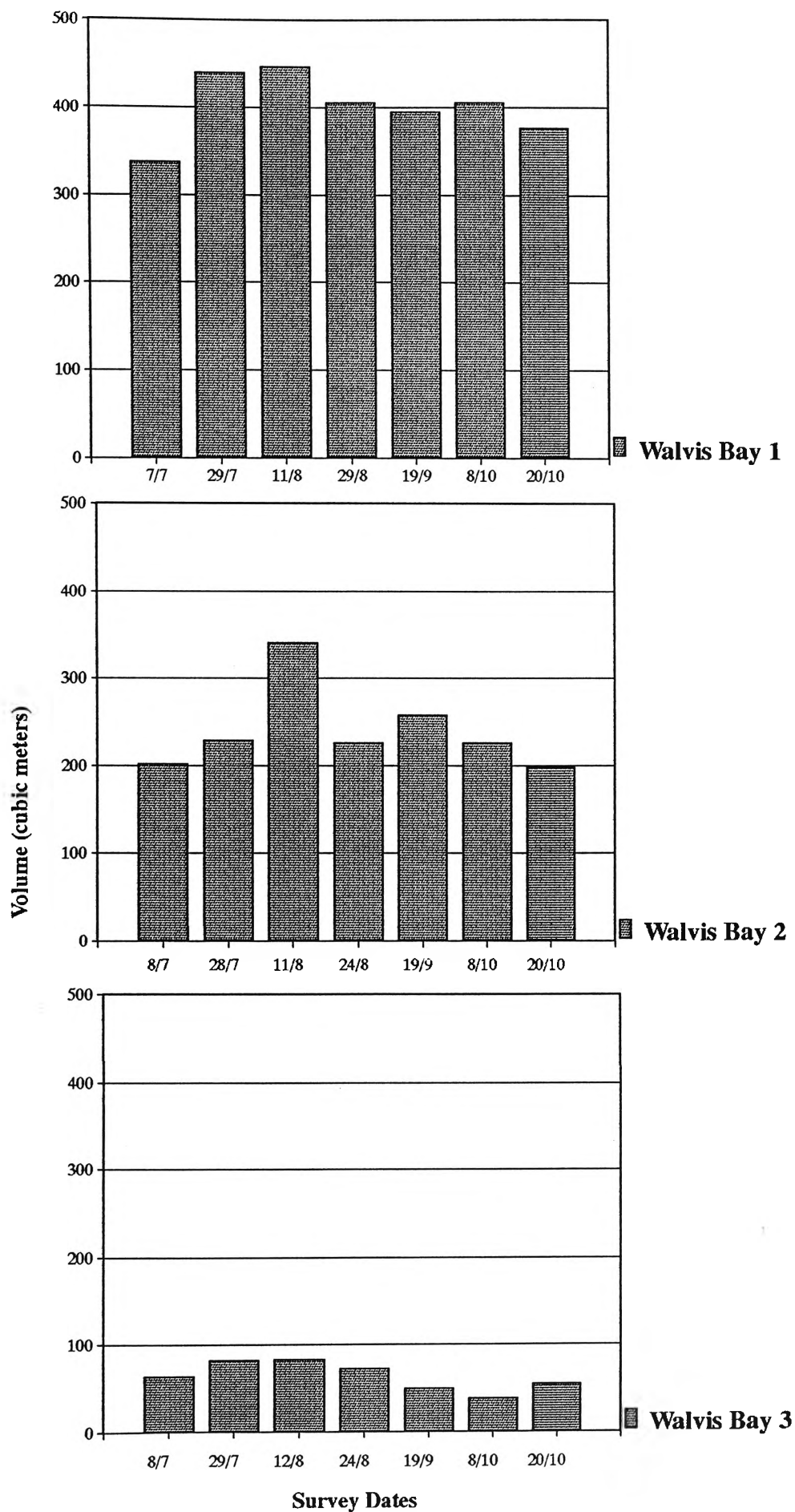


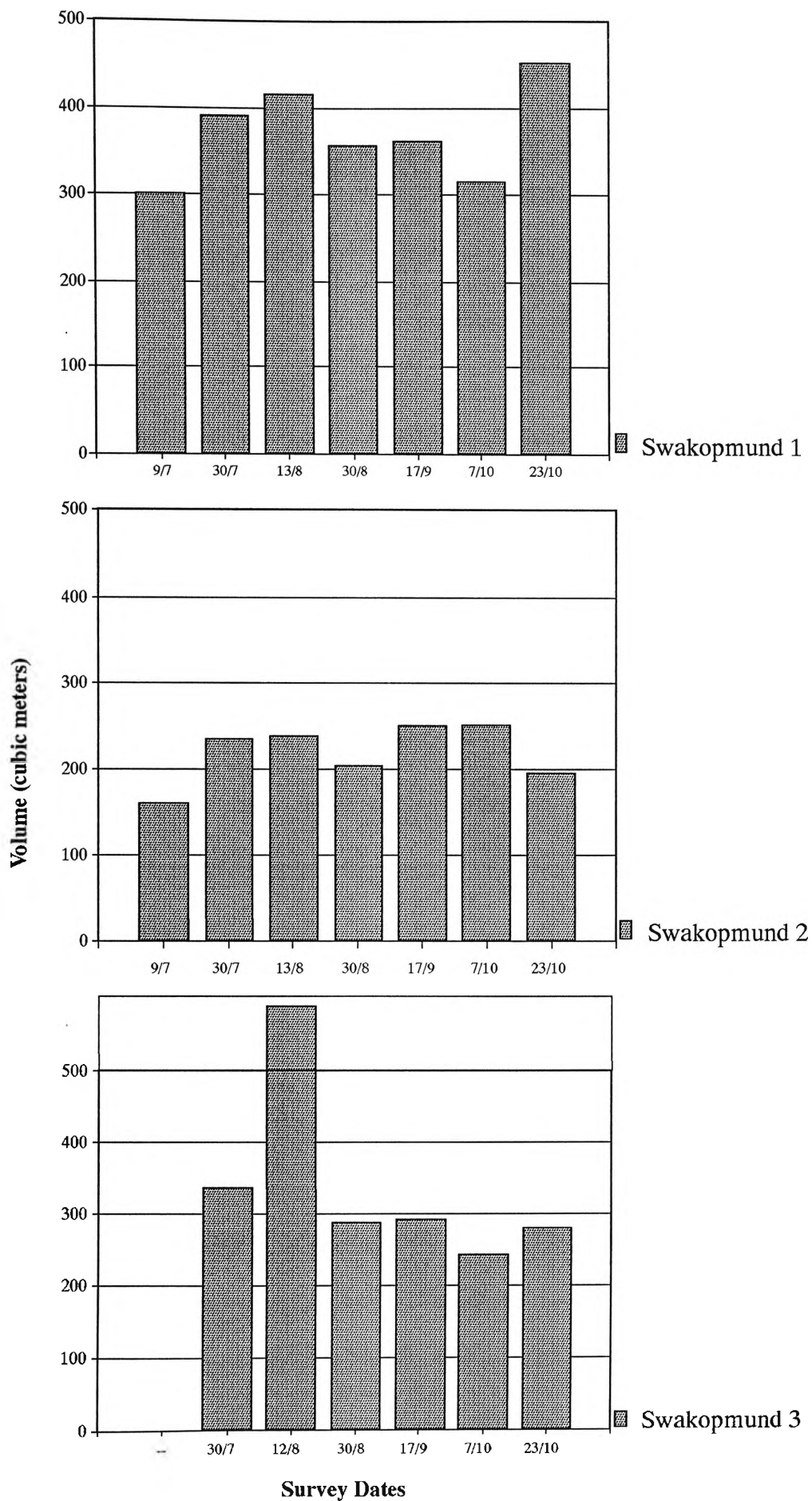
Figure 4.6 Dune volume at Walvis Bay

had an overall decrease of 1%. The volume of sand contained in the dune and the change in volume over time are very much dependent on available sand supply and exposure to sand-transporting winds. WB1 and WB2 are located within close proximity to the main dunefield while WB3 is comparatively isolated from potential sand sources. However, all the dunes are located within 1km of each other, implying that the controls on dune volume are strongly localized. In addition, volume changes indicate that sand supply must have been significantly greater for all dunes during an easterly or northeasterly wind, as evidenced by the marked increase in volume for the dunes subsequent to the easterly storm in July. Alternatively, the extremely high wind velocities associated with this easterly storm would have resulted in a greater amount of sand transport, irregardless of wind direction. Even minor shifts in velocity and direction are manifested in dune movement and volume. For example, Lettau and Lettau (1969) observed that an increase of 20% in wind velocity at a height of 320cm could increase bulk transport rates by 50-100%. Wind direction and velocity, combined with available sand supply, therefore, are the most important factors in explaining these dune volume fluctuations.

#### 4.5.2 Dune volume at Swakopmund

The Swakopmund dunes were located within 150m to one another. All Swakopmund dunes show an increase in volume over July and August, which decreases at the end of August (Fig. 4.7). Following the easterly storm wind of 21 July, volume increased for SW1 and SW2 (no pre-easterly survey data is available for SW3). Volume decreases for all dunes from mid-August until early September, with SW3 showing the largest drop in volume over this period ( $300 \text{ m}^3$ ), compared to  $60 \text{ m}^3$  for SW1 and  $34 \text{ m}^3$  for SW2. The calculated volume for SW3#2 ( $589.33 \text{ m}^3$ ) appears to be unfeasibly high. The data were checked for possible errors in calculation or data entry but none were detected.





**Figure 4.7 Dune volume at Swakopmund**

SW1 exhibited an increase in volume during the latter half of October, and also had a volume increase of 34% over the entire survey period. SW3, too, showed a minor increase over the same period, but had an overall 21% decrease in volume. SW2 decreased in volume during October, but exhibited an overall volume increase of 18%.

In terms of sand supply, dune location, relative to the surrounding dunes, is a significant factor in the analysis of volume fluctuations. Norris (1965) found that in the Tule Wash area, decreases in volume were attributable to decreased availability of sediment, due to flooding of the adjacent drainage area. In addition, frequency and duration of strong cross-winds were cited as having a possible control on volume fluctuations, but it was not possible to quantify these effects in the absence of wind data.

SW1 is located directly to the northeast of a large transverse dune, approximately 5m upwind; under a southwesterly or westerly wind regime, this dune would provide a consistent source of sand, as indicated by the 34% increase in volume over five months. SW2 had an 18% increase in volume over the same time period. By comparison, SW3 experienced a 17% decrease in volume under these prevailing wind conditions. As SW3 was situated directly upwind of SW2, it potentially provided a small sand source to SW2, particularly since the increase in SW2 volume is almost identical to that lost from SW3.

#### 4.5.3 Comparison of the Swakopmund and Walvis Bay Dunes

As the study sites are situated approximately 40 km apart, any statistically significant similarities in local sand transport and subsequent dune volume fluctuation would be unexpected. With the exception of SW1#1, both the Walvis Bay dunes and the Swakopmund dunes show similar patterns in volume changes. Volume increases until mid- to late August, remaining fairly steady until the end of October. The greatest change in volume at

Swakopmund was a 34% increase (SW1), whilst at Walvis Bay the greatest change was WB3, with a 13% decrease.

The Swakopmund dunes indicated a greater degree of volume fluctuation when compared to Walvis Bay. This variability may be attributable to locational differences and the effect these differences have on sediment transporting ability and available sand supply. It has been previously observed that changes in dune volume are attributable to wind or sand-supply conditions (Lettau and Lettau, 1969; Hastenrath, 1987). The Swakopmund dunes were located adjacent to a large transverse dunefield, which under certain wind directions acted as a significant source of sediment to the 'domes'. By contrast, the Walvis Bay dunefield was an open plain with no immediate significant sand source. Subsequent to the easterly storm winds, sand supply here was comparatively steady.

Changes in the direction of displacement did not correlate with volume fluctuations in either study area after the end of August. Volume increased between survey period 1-2, after the easterly storm. In August (survey 3-4), all the dunes re-aligned towards the northeast. Over the same period, a marked decrease in volume occurred for all dunes. As migration continued in this direction, volume fluctuations did not appear to follow any consistent pattern.

The shifts in wind direction, combined with available sediment supply, may have influenced these changes in volume. Sand supply, particularly for the Walvis Bay dunes, was limited under a southwesterly or southeasterly wind regime, which may explain why volume for these dunes remained relatively steady over this period. The Swakopmund dunefield, due to the adjacent transverse dunes, would have had a steady supply of sediment under a southwesterly/southeasterly wind regime, as indicated by the increases in volume for SW1 and SW2.

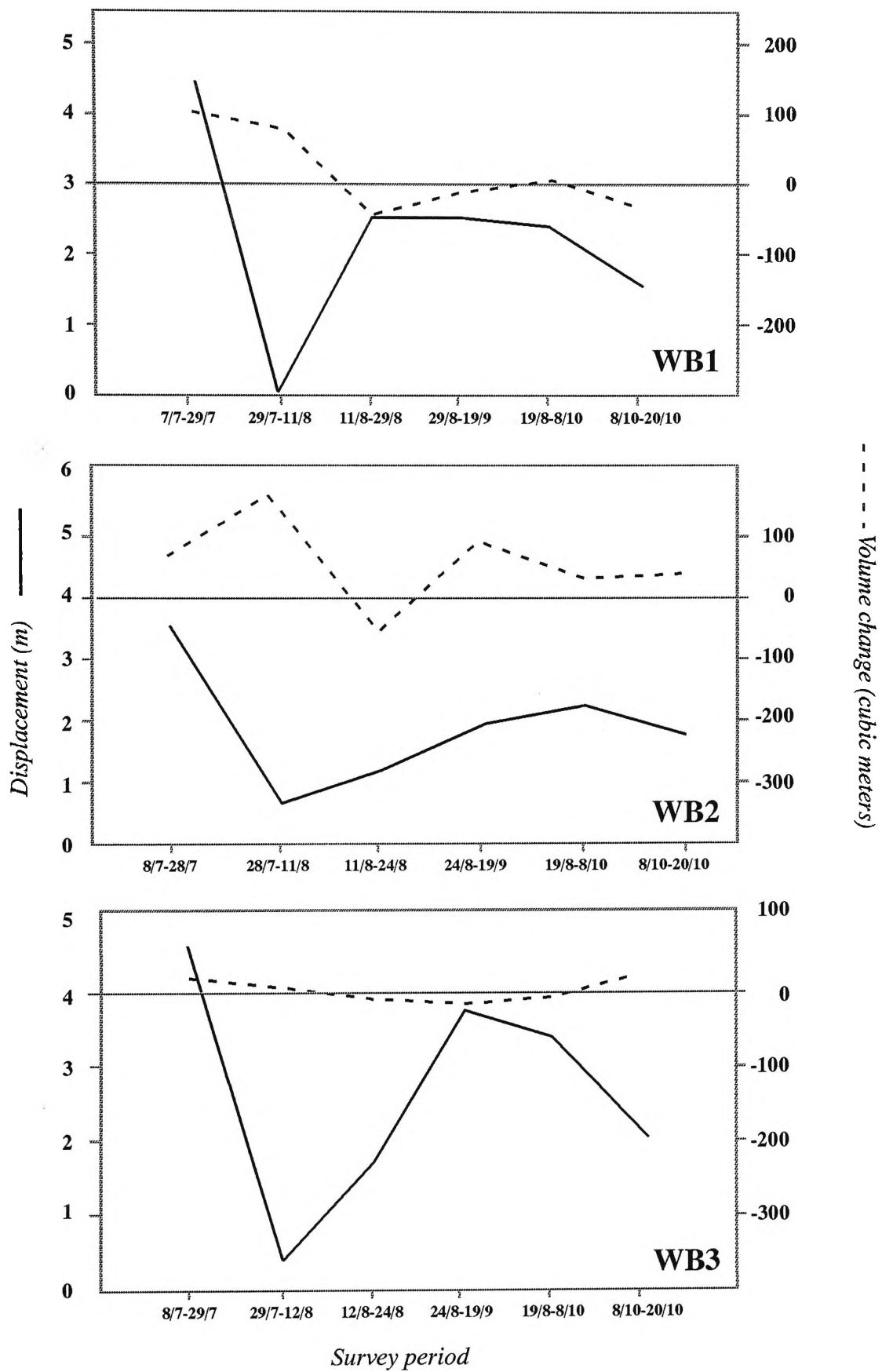
Both long term and short term wind intensity and direction, with the resulting sand transport, appear to be responsible for the differences and patterns of change in the dunes. The high intensity, short duration easterly storm wind of 21 July resulted in a noticeable increase in volume for all dunes. Over the remainder of the survey period, volume decreases irregularly from August (Fig 4.6) in the Walvis Bay dunes, as winds become predominantly southeasterly, shifting towards the south during the latter part of the survey period. As mentioned above, Swakopmund dunes do not appear to follow any consistent pattern in terms of volume changes, and volume changes do not correlate with changes in wind directions.

A detailed analysis of wind velocities and directions and dune migration follows in Chapter Six.

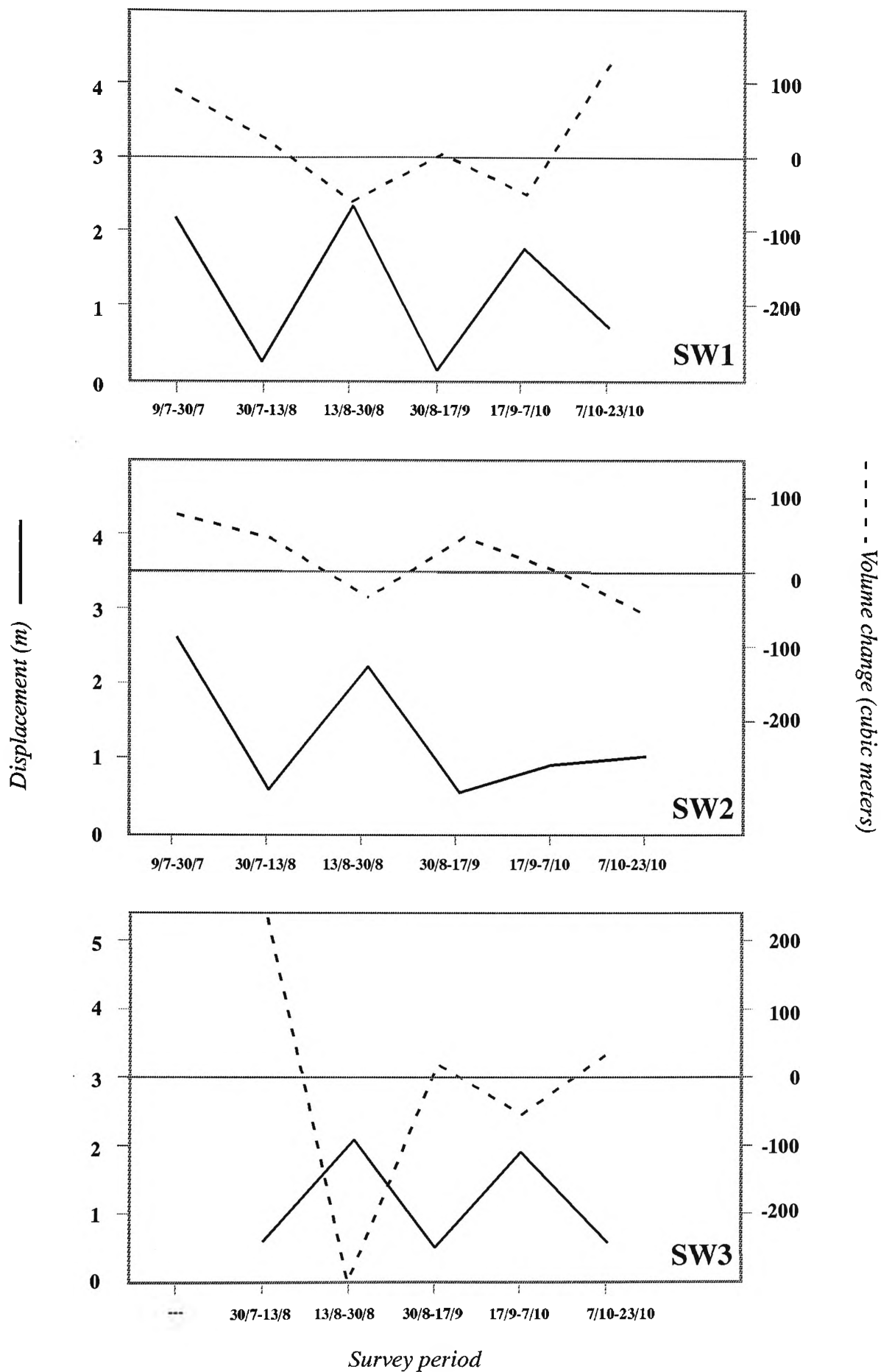
#### 4.5.4 Dune Volume and Migration

Figure 4.8a and 4.8b illustrates the relationship between dune size (volume) and migration. The graphs show the change in volume between surveys, plotted against actual dune movement over the same period. In general, the trends for all dunes are consistent; however, Swakopmund dunes show a slightly better (non-statistical) correlation between volume and migration for some survey times. When dune volume has increased, dune migration has decreased, as indicated by other studies.

Since many previous studies have been carried out in apparent uni-directional wind regimes, and barchans mostly migrate in one direction (at least in the long term), it was considered that an assessment of dune migration in a consistent direction may provide a better indication of a potential relationship between migration and volume changes. From mid-September to the end of October (survey 6 to 7), the Walvis Bay dunes migrated in a northeasterly direction and maintained a reasonably consistent shape. This uni-directional movement was plotted against



**Figure 4.8a** Volume change and displacement at Walvis Bay



**Figure 4.8b Volume change and displacement at Swakopmund**

volume. Volume measurements do not exhibit any obvious pattern of change, with some dune volumes increasing and others decreasing over this 6-7 survey period.

Norris (1965) observed that barchans show little or no correlation between volume change and rate of movement over short periods, such as one month. It is apparent from the graphs of the Namib data (Fig. 4.8a and 4.8b) that this is not always true, given the slight negative graphical relationship between these variables. Two points are worth mentioning regarding this relationship; firstly, the point where the baseline is measured and used for determining displacement varies with different workers. The base of the slipface is the accepted point of measurement when determining movement. This is true in Norris' case as well, in his discussion of the relationship between migration and volume. Displacement for the Namib dunes was based on a mathematically-derived centre point (see Chapter 3), because much of the time a slipface either did not exist, or the dunes were too irregular in shape to determine visually an accurate point of measurement. The differences in the determination of this point may be manifested in the measured displacement rates. In this case, the slight correlation between displacement and volume, where displacement is based on the calculated centre point as the point of measurement, indicates that, even over short measurement periods, there is still a measureable relationship between these variables at times, as indicated in Figure 4.8a and 4.8b.

The second aspect of this relationship is the volume calculations themselves. The volume calculations of the Namib dunes were done by computer, based on the results of highly detailed field surveying. During the time that the previous studies of dune volume were conducted, this computer technology was either non-existent, or not widely available. As a result, volume calculations often contained a comparatively high level of inaccuracy, as Norris (1965) and Petrov (1976) both state. Often, this methodological inaccuracy was not acknowledged, thereby leading to assumptions of relationships based on the use of questionable data. Lettau

and Lettau (1969, p. 184) computed dune volume in their study of the Peruvian barchans. To compute this volume, they assumed that the barchan is "perfectly symmetric" with respect to its longitudinal axis. Although the Peruvian barchans represent examples of barchans of near classic shape, this is not the case in many areas around the world. None of the Namib dunes exhibit perfect symmetry at any time. Therefore, a volume calculation based on an assumption of symmetry may provide unreliable results.

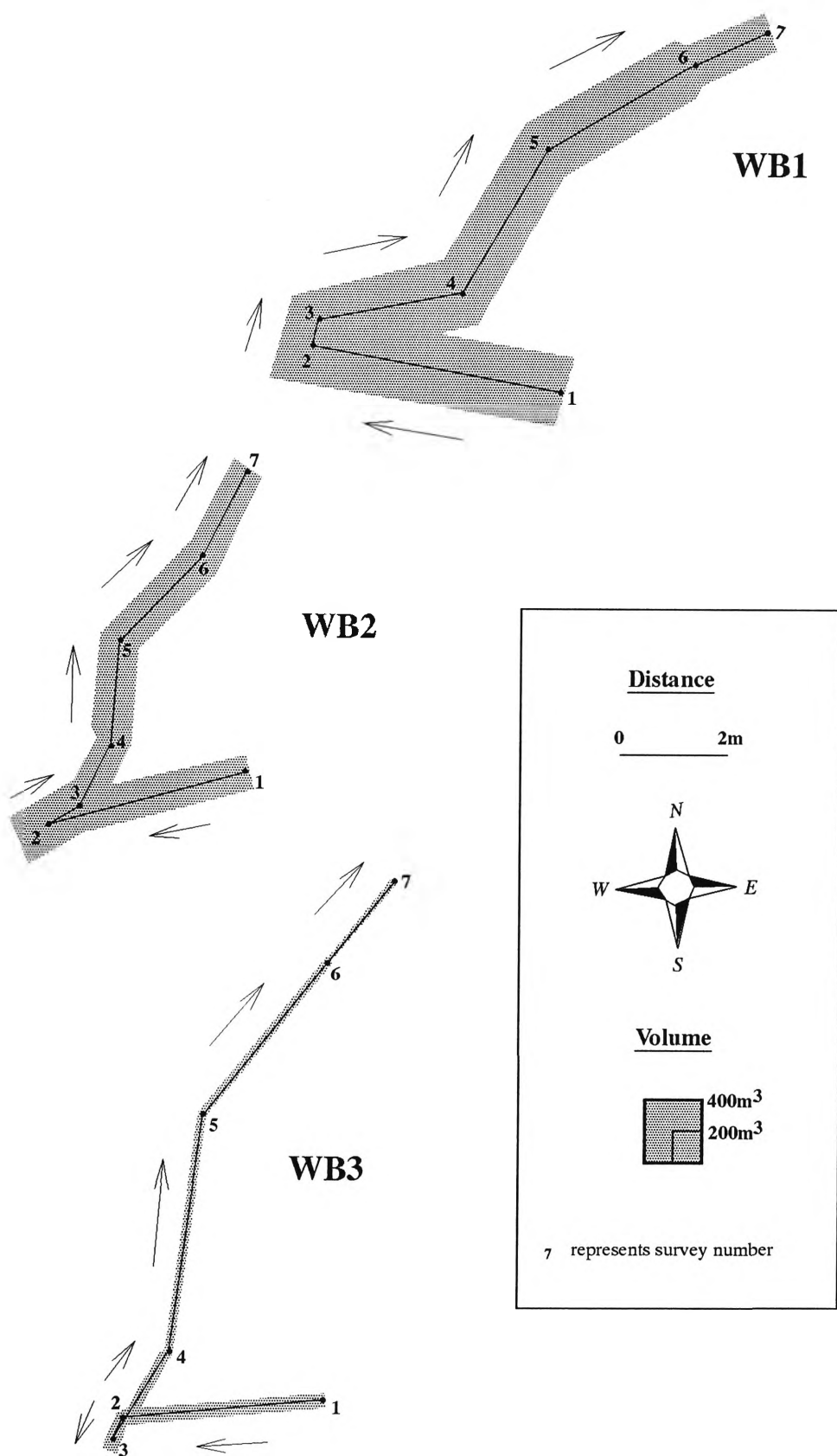
Figure 4.9a and 4.9b summarize dune volume and displacement, and incorporates direction in the representation. From this graph, the dune size differences are obvious, based on volume calculations, especially for the Walvis Bay dunes. The Walvis Bay dunes exhibit a much higher amount of total displacement, when compared to the Swakopmund dunes, which moved very little, in fact. The Swakopmund dunes, however, are smaller than Walvis Bay (with the exception of WB3), if volume is used as an indication of size.

#### 4.5.6 Conclusions

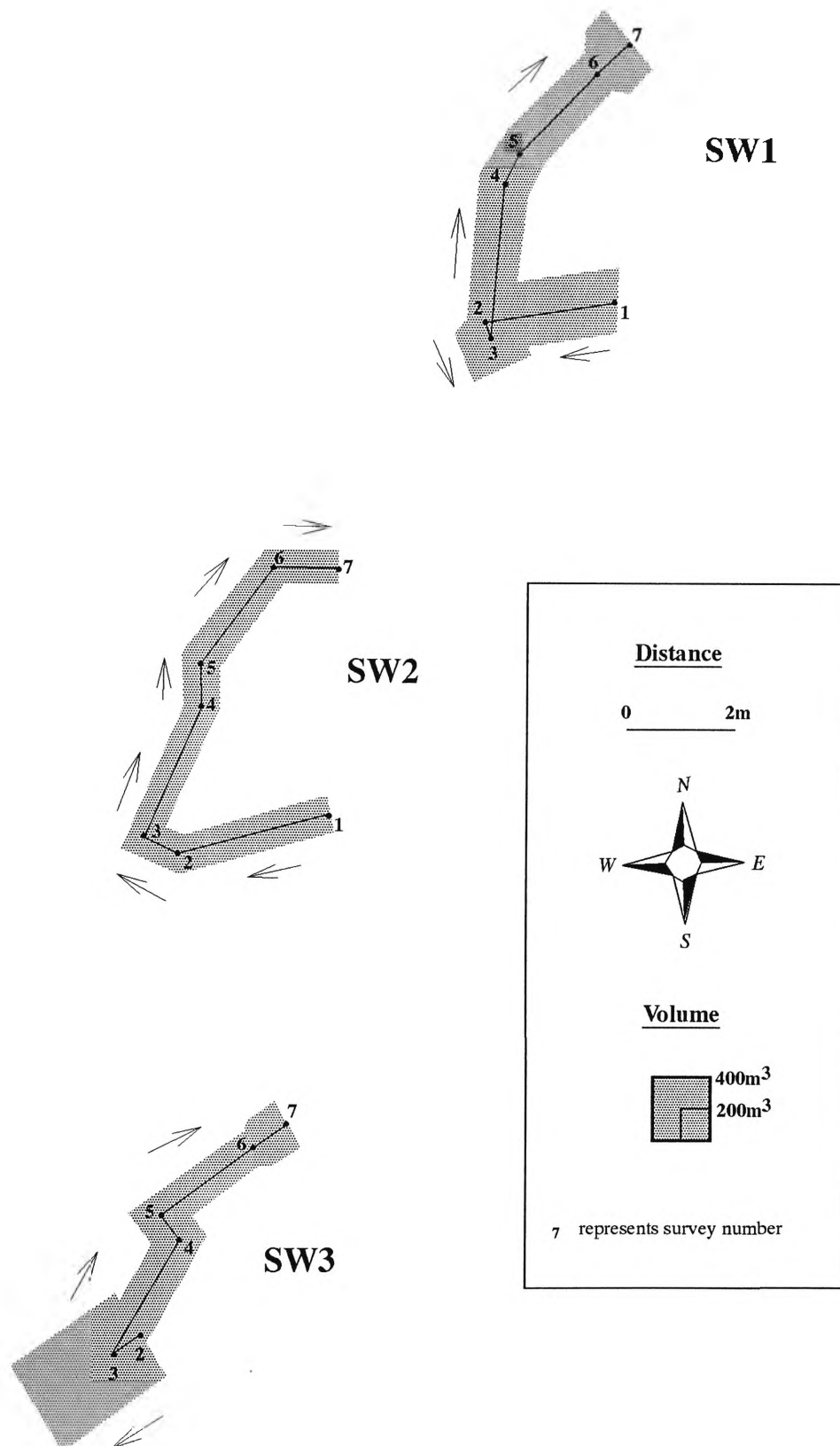
It is concluded from this study of dune migration (displacement) and volume, that:

(1) Migration directions are reasonably similar for all dunes, with significant movement towards the west occurring as a result of the easterly storm. Displacement drops off markedly during the remainder of the survey period. Displacement direction also shifted towards the northeast over the same period. Displacement rates vary as a result of exposure to sand-transporting winds. Assuming that the dune is exposed to these winds, there must be sufficient sediment available for transport and deposition. In the case of Walvis Bay, exposure to the strongest winds was high; however, sediment supply was not as abundant as at Swakopmund, with its adjacent transverse dunefield. Although sediment was in large supply, exposure to strong sand transporting winds in the Swakopmund area was not significant.





**Figure 4.9a Migration direction and distance, and volume for the Walvis Bay dunes**



**Figure 4.9b Migration direction and distance, and volume for the Swakopmund dunes**

These dunes lie within close proximity to one another; therefore, localized inconsistencies in flow and sediment transport, combined with dune size, result in differences in displacement rates and the direction of displacement and dune shape.

(2) Dune volume increases dramatically during the post-easterly storm period, then fluctuates in no apparent pattern throughout the remainder of the survey period. SW3 exhibits very marked fluctuations in volume, particularly between survey 2 and 3. During this time, wind direction shifted towards the northwest; since SW2 was directly to the south of SW3, it is possible that SW2 provided a moderate sediment source to SW3 under these wind conditions.

(3) Dune volume change exhibits some limited (non-statistical) association with displacement, i.e. as volume decreases, movement increases in a few cases. This is apparent in the case of the Swakopmund dunes for part of the time. Walvis Bay dunes do not correlate well, particularly WB3. WB3 volume change, compared to WB1 and WB2, was not as significant; however, its total overall volume, and therefore size, was much less, indicating a higher amount of movement is not unexpected.

(4) Several differences in the relationship between volume and displacement between Swakopmund and Walvis Bay are apparent. These differences may in part be attributable to variations in dune characteristics, such as grain size and baseline dune height, and the relationship of these differences on effective wind velocities and sediment transport. In the case of Swakopmund, the lack of exposure to strong winds, combined with larger, heavier sediment resulted in a lower amount of displacement when compared to Walvis Bay. Since volumes were similar for both areas (with the exception of WB3), it is apparent that the inconsistencies are attributable to the abovementioned factors.

This chapter has presented reliable, accurate volume calculations, based on detailed maps obtained from a series of topographic surveys. To date, no other study has achieved this. Because of the difficulty in obtaining accurate volume data in previous studies, dune height was most often chosen as an indicator of size. This study has shown that dune volume should be incorporated in the determination of dune size, particularly if that data are to be employed in the determination of relationships between a variety of factors. Two previously accepted observations have been shown by the data presented as part of this thesis, to be somewhat questionable. These observations have been mentioned in the above sections to various degrees, but will be summarized here.

(1) Shape varies with dune size; as height increases, dune shape tends to flatten (Hastenrath, 1967). This may be true when slipface height is used as the measurement of dune size. Swakopmund dunes are lower in height compared to Walvis Bay, implying that they are therefore flatter in shape. But they are not smaller when volume is taken into account, as both Tables 4.1 and 4.2 and Figures 4.5 and 4.7 indicate. Volumes are fairly similar, except for WB3.

(2) Shape appears to depend on dune size, with only larger dunes exhibiting a classic barchan shape (Hastenrath 1967, Lettau and Lettau 1969). WB1, and to a large extent WB2, with dune heights greater than any other of the dunes but still considered small by Hastenrath's criteria, attain a classic asymmetric or symmetrical shape towards the end of the survey period. In addition, the Swakopmund dunes, although having markedly lower slipface heights, when volume is considered, are very similar in size to WB1, but do not exhibit similar shape characteristics.

The final point regarding volume calculations is that because these data have not been easily obtained in the past, does not imply that, by default, size determined from slipface height alone

should be taken as totally representative of true size. With the advent of new methods of obtaining and calculating accurate volume data, it is imperative that the accepted relationships between height, volume, and displacement be reviewed, and that volume calculations become recognized as fundamental in the proper determination of dune size.

The relationship between dune size and displacement is not independent of the effects of wind velocity and direction, and short-term sediment supply. Dune size and displacement operate in conjunction with certain geometric parameters, such as dune height and width between dune horns. These additional factors influence, or are affected by, dune movement to a greater or lesser degree. In subsequent chapters, these other factors will be considered in detail, particularly with respect to their effect on dune movement and volume changes over time.

## Chapter 5

# MORPHOMETRICS

### 5.1 INTRODUCTION

The relationship between dune height and displacement has been studied extensively (Finkel, 1959; Hastenrath, 1967, 1983; Coursin, 1964; Long and Sharp, 1964). These earlier studies have attempted to establish that a significant statistical relationship exists between height and displacement, and between displacement and volume. These studies, without exception, neglected to adequately report the statistical significance of the results. Discrepancies in results are explained by a variety of other factors, described in subsequent sections of this chapter.

Geometric relationships between barchan height, distance between the dune horns, and dune size have been established (Mabbutt, 1977; Finkel, 1959, Hastenrath, 1967; Lettau and Lettau, 1969) and have been shown to be reasonably consistent. These relationships have been based on barchans with reasonably symmetrical morphology. Finkel (1959) observed that distance between the horns closely correlated with slipface height. He subsequently used this relationship to derive displacement rates. Mabbutt (1977) also found that dune height was consistently 1/10 of the width.

The most fundamental observation, that dune displacement decreases with dune height, also (presumably) assumes symmetrical dune morphology. The corollary of this relationship, that small dunes move more quickly than larger ones, has been "established beyond all reasonable doubt" (Cooke et al., 1993, p. 339). As with the majority of dune size relationships, dune height is again used as the primary indicator of size.

This chapter discusses the dune displacement, height and volume relationships for the Swakopmund and Walvis Bay dunes, compares these results with previous studies, and examines the validity of the conclusions based on statistical analysis.

## 5.2 DUNE HEIGHT vs. DISPLACEMENT

Dune height and displacement were plotted for both Walvis Bay and Swakopmund dunes to determine if a relationship exists between dune height and rate of movement, as indicated by many previous authors. Slipface height was obtained from the field notes made during the topographic surveys. If no slipface existed, then dune crest height was used. A slipface was present in all dunes most of the time. Since displacement was calculated between survey periods, an average slipface (or dune) height was determined for the two survey periods from the data shown in Table 5.1. These data were then graphed and a statistical correlation between the two variables determined through regression analysis. The results are compared to previous studies of the relationship between dune height and displacement rate undertaken by other workers (Hastenrath, 1967; Finkel, 1959; Long and Sharp, 1964).

The statistical summaries of the Walvis Bay and Swakopmund data are shown in Table 5.2. These data were pooled in order to supplement the small sample size. Included in the pooled data summaries are the regression equations, the t-statistic, the  $r^2$  value and  $r^2$  value adjusted for degrees of freedom. Based on the statistics for pooled height and displacement data, changes in displacement are not significantly explained by changes in height. The diagnostic statistics calculated for the average values indicate that only 11% of the variation in displacement is explained by changes in height. The adjusted  $r^2$  value shows even less of a relationship. The t-statistic of 0.73 is less than the minimum required (greater than or equal to 2) to indicate the existence of a significant relationship between these variables, i.e. the

## Walvis Bay

Dune	Dune Ht (m)	Disp. (m)	Dist. bet. Horns (m)	Volume (m <sup>3</sup> )
WB1/1	1.2	4.5	16.5	337
WB1/2	1.3	0.5	--	439
WB1/3	1.6	2.6	--	447
WB1/4	1.5	2.6	15.0	405
WB1/5	1.4	2.5	20.5	395
WB1/6	1.3	1.6	15.0	405
WB1/7	1.5		15.0	376
WB2/1	1.0	3.5	13.0	201
WB2/2	1.1 *	0.6	14.5	229
WB2/3	1.3 *	1.2	--	341
WB2/4	0.9	1.8	14.0	226
WB2/5	0.9	2.1	15.0	257
WB2/6	0.9	1.6	12.0	226
WB2/7	1.2		11.0	198
WB3/1	0.6 *	4.6	--	64
WB3/2	0.6 *	0.4	10.0	82
WB3/3	0.6 *	1.7	10.0	83
WB3/4	0.6 *	3.7	--	72
WB3/5	0.5	3.4	10.0	49
WB3/6	0.5	2.0	7.0	38
WB3/7	0.5 *		6.0	55

## Swakopmund

Dune	Dune Ht (m)	Disp. (m)	Dist. bet. Horns (m)	Volume (m <sup>3</sup> )
SW1/1	1.3 *	2.2	--	300
SW1/2	1.4 *	0.25	16.5	391
SW1/3	1.4 *	2.35	16.5	416
SW1/4	0.8	0.5	18.0	356
SW1/5	1.0	1.8	21.0	362
SW1/6	0.3	0.75	19.5	315
SW1/7	1.2 *		17.0	453
SW2/1	1.1 *	2.7	--	160
SW2/2	0.8	0.6	13.0	234
SW2/3	0.7	2.2	13.0	238
SW2/4	0.7	0.7	16.5	204
SW2/5	0.3	2.0	18.0	249
SW2/6	0.4	1.1	14.5	250
SW2/7	0.4		13.5	195
SW3/2	1.0	0.65	12.0	336
SW3/3	0.9	2.1	15.5	589
SW3/4	0.9	0.55	15.0	288
SW3/5	0.6	1.95	15.5	291
SW3/6	0.4	0.6	13.0	240
SW3/7	0.5		13.0	280

Dune height represents the highest point of the dune, if a slipface was not present.  
 \* represents height measurement based on dune height, not slipface height

**Table 5.1 Morphometric data, Namib dunes**



### Height vs. Displacement \*

Swakopmund	$D = 0.85 + 0.64H$	$r^2 = 0.04$
Walvis Bay	$D = 2.64 - 0.39H$	$r^2 = 0.01$
Pooled data	$D = 1.22 + 0.73H$	$r^2 = 0.04$
	$t = 1.30$	$r^2 = 0.02$ #

### Height vs. 1/Displacement \*

Pooled data	$D = 0.99 - 0.03H$	$r^2 = 0.00$
	$t = -0.08$	$r^2 = -0.03$ #

### Volume vs. Displacement \*

Swakopmund	$D = 1.54 - 0.0008V$	$r^2 = 0.08$
Walvis Bay	$D = 2.64 - 0.001V$	$r^2 = 0.03$
Pooled data	$D = 2.45 - 0.005V$	$r^2 = 0.06$
	$t = -1.50$	$r^2 = -0.04$ #

### Volume vs. Height \*

Swakopmund	$H = 0.45 + 0.0007V$	$r^2 = 0.05$
Walvis Bay	$H = 0.39 + 0.002V$	$r^2 = 0.88$
Swakopmund	$V = 259.7 + 72H$	$r^2 = 0.05$
Walvis Bay	$V = 2.3 + 1.8H$	$r^2 = 0.88$
Pooled data	$V = 141 + 171H$	$r^2 = 0.24$
	$t = 3.26$	$r^2 = 0.22$ #

\* Significant at the 5% level.

# adjusted  $r^2$

**Table 5.2 Height, volume and displacement data - Namib dunes**

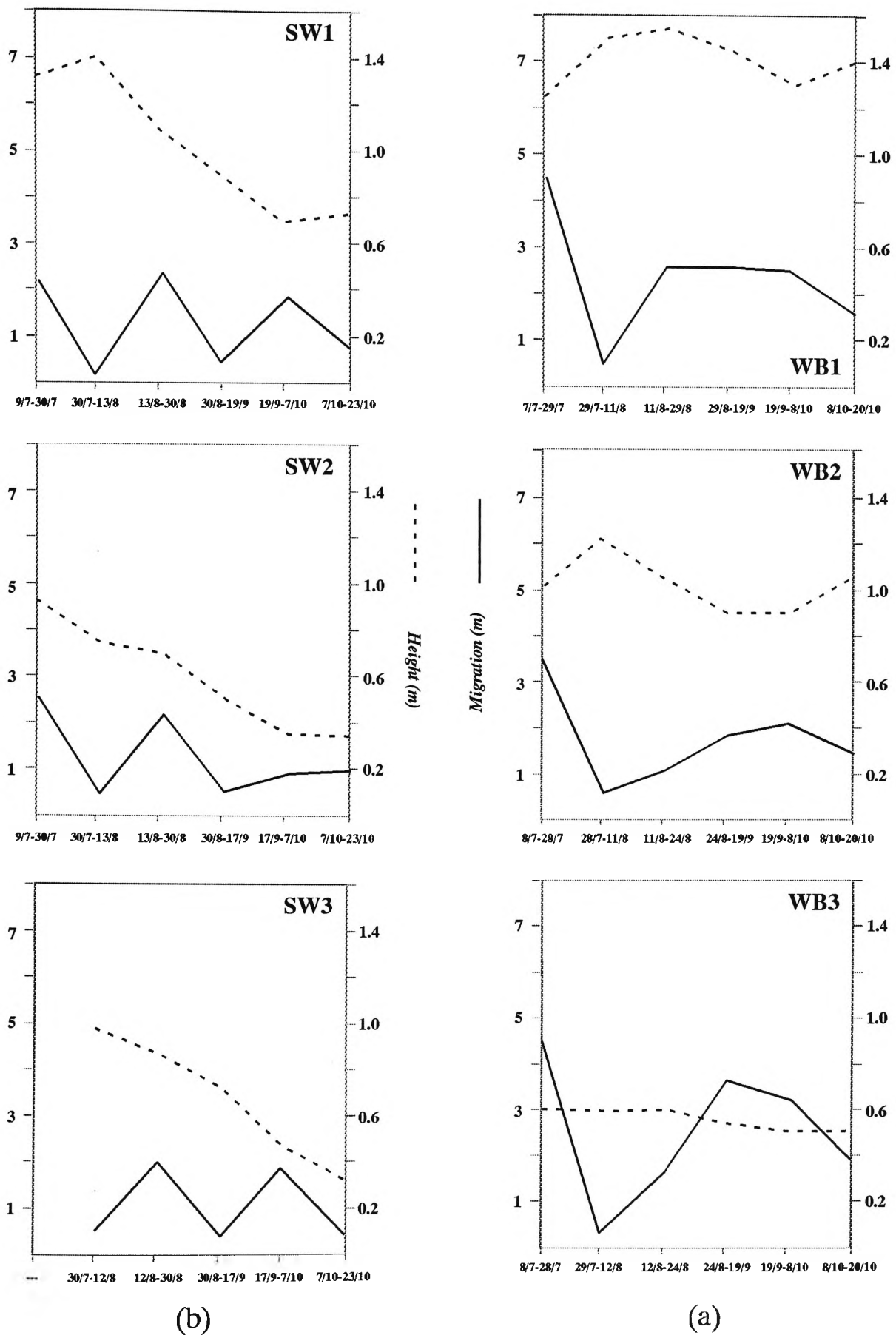
coefficient of the independent variable (H) is not significantly different from zero at the 5% level.

Prior to the statistical analysis, a graphic representation illustrating the relationship between height and displacement was prepared (Fig. 5.1) which shows that in some instances, decreases in height correspond slightly to increases in displacement, particularly for WB1 and WB2, although results of the statistical analysis for the Walvis Bay dunes indicate there is no significant relationship between dune height and displacement (Fig. 5.2a). Slipface height only varies 1m between each of the three dunes, and although height differences are minimal, variation in total displacement ranges from 0.5m to 4.5m. In real terms, each dune appears to maintain a reasonably consistent slipface, or dune, height but the amount of displacement between the Walvis Bay and Swakopmund dunes varies markedly. In contrast to the Walvis Bay dunes, the three Swakopmund dunes are similar in size and rate of movement, as illustrated in Figure 5.2b.

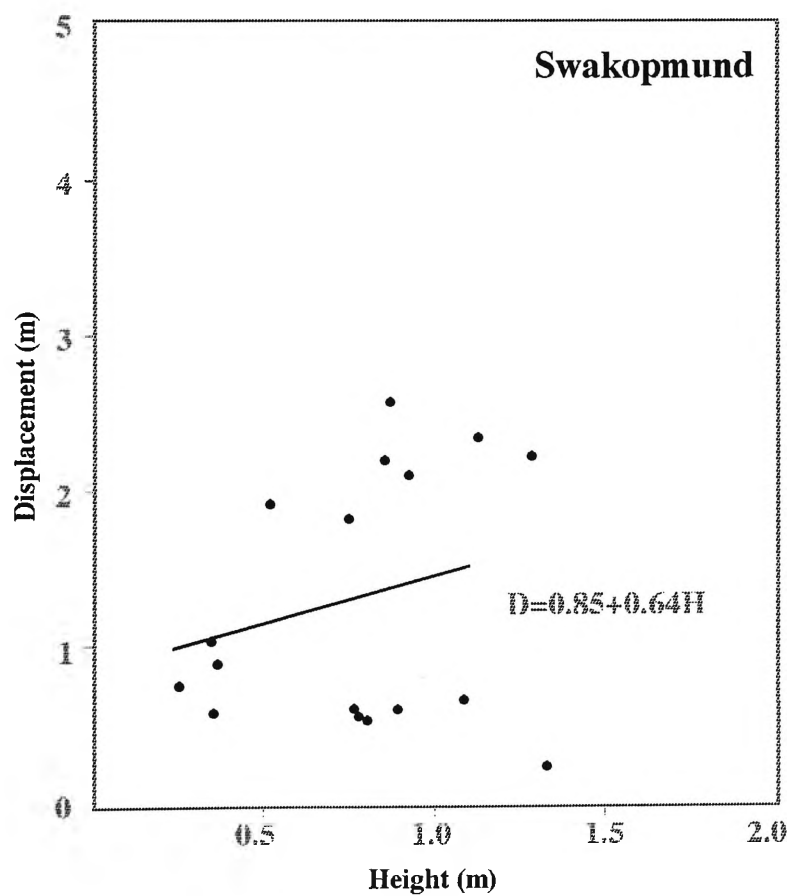
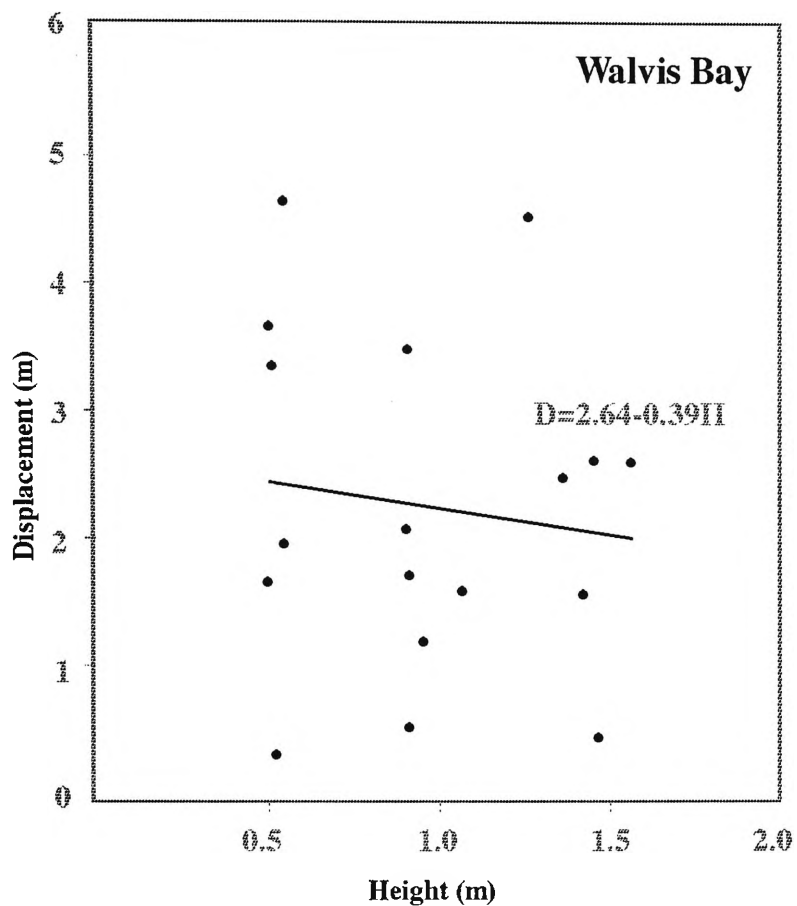
The results were also determined for height and the reciprocal of displacement ( $1/D$ ) (Table 5.2). Similar to the linear relationship, results were inconsistent, but overall no significant correlation was established, given that both the  $r^2$  and adjusted  $r^2$  values were low, together with the low t-statistic. It is concluded that there is no linear relationship that can be shown to be statistically significant between dune height and displacement.

In an attempt to achieve a better correlation with previous studies, particularly with Hastenrath's data, the Walvis Bay and Swakopmund data were re-plotted in a number of ways. Figures 5.3 - 5.5 present the results of these plots.

Dune displacement in this study was estimated by first mathematically determining a dune centre point (Chapter 3). This method incorporates volume in the calculation. In all previous



**Figure 5.1** Graphs depicting the non-statistical relationship between dune height and displacement, Namib dunes



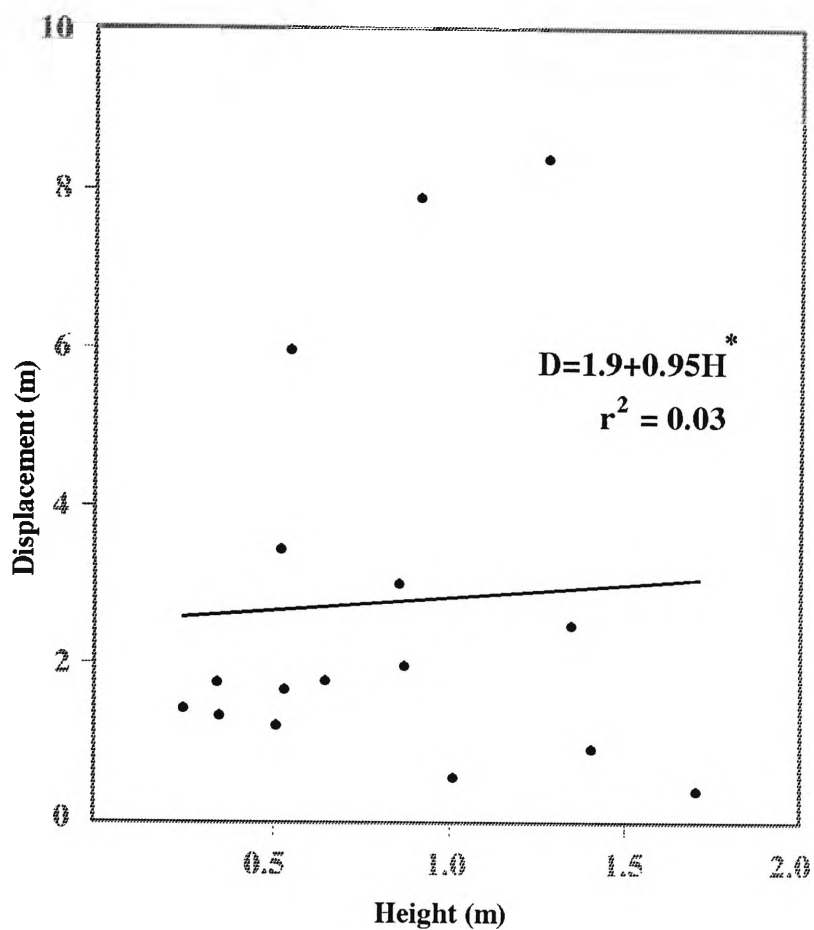
**Figure 5.2** Graphs depicting the statistical relationship between height and displacement, Namib dunes

displacement studies movement was determined using the base of the slipface, or downwind edge, of the dune. Since the centre-point method was different, the Namib dunes were re-plotted using the position of the slipface base as the measuring point, to make the data comparable to the earlier studies. In addition, only those dunes which exhibited true forward displacement and were of a regular shape were plotted. Figure 5.3 indicates the results, which show that no significant relationship exists at the 5% level between dune height and forward displacement.

As a comparison, forward displacement derived from the centre-point method was also graphed against height. Figure 5.4 includes the graphed results, which indicate that the relationship between height and forward displacement is not significant at the 5% level.

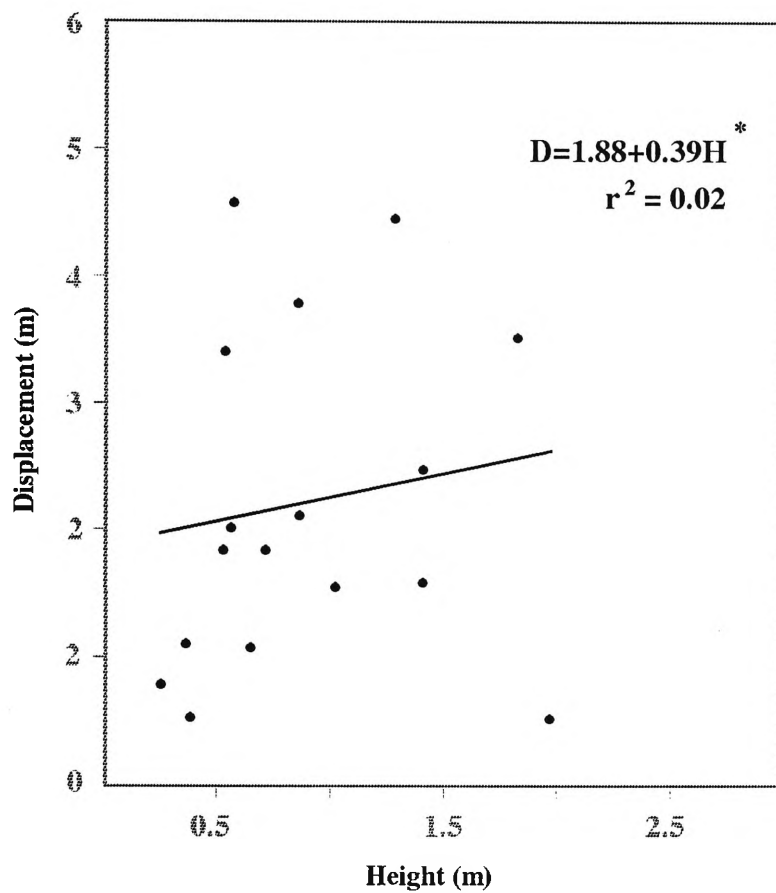
Figure 5.5 shows displacement and height for both Walvis Bay and Swakopmund dunes, using mean height for the entire survey period plotted against total displacement over the same period. As with the previous results, the relationship is not significant at the 5% level.

Given the poor correlation between dune height and displacement, the data were re-examined to determine if using dune height instead of slipface height may have influenced the results. It was found that dune height and slipface height at Swakopmund exhibited marked differences. Average slipface height for each dune was consistently less than the average dune height as much as 51% for SW2. The Walvis Bay dunes did not show as much variation between average dune height and average slipface height, with dune height being approximately 26% more than slipface height for WB1 and WB2. The data were re-examined by measuring the dune height (the highest point of the dune) and plotting this against displacement for both the Walvis Bay and Swakopmund dunes. The regression analysis indicates that using dune height in preference to slipface height does not significantly affect the results. It is implied from these results that the difference in slipface/dune height ratio between Walvis Bay and Swakopmund



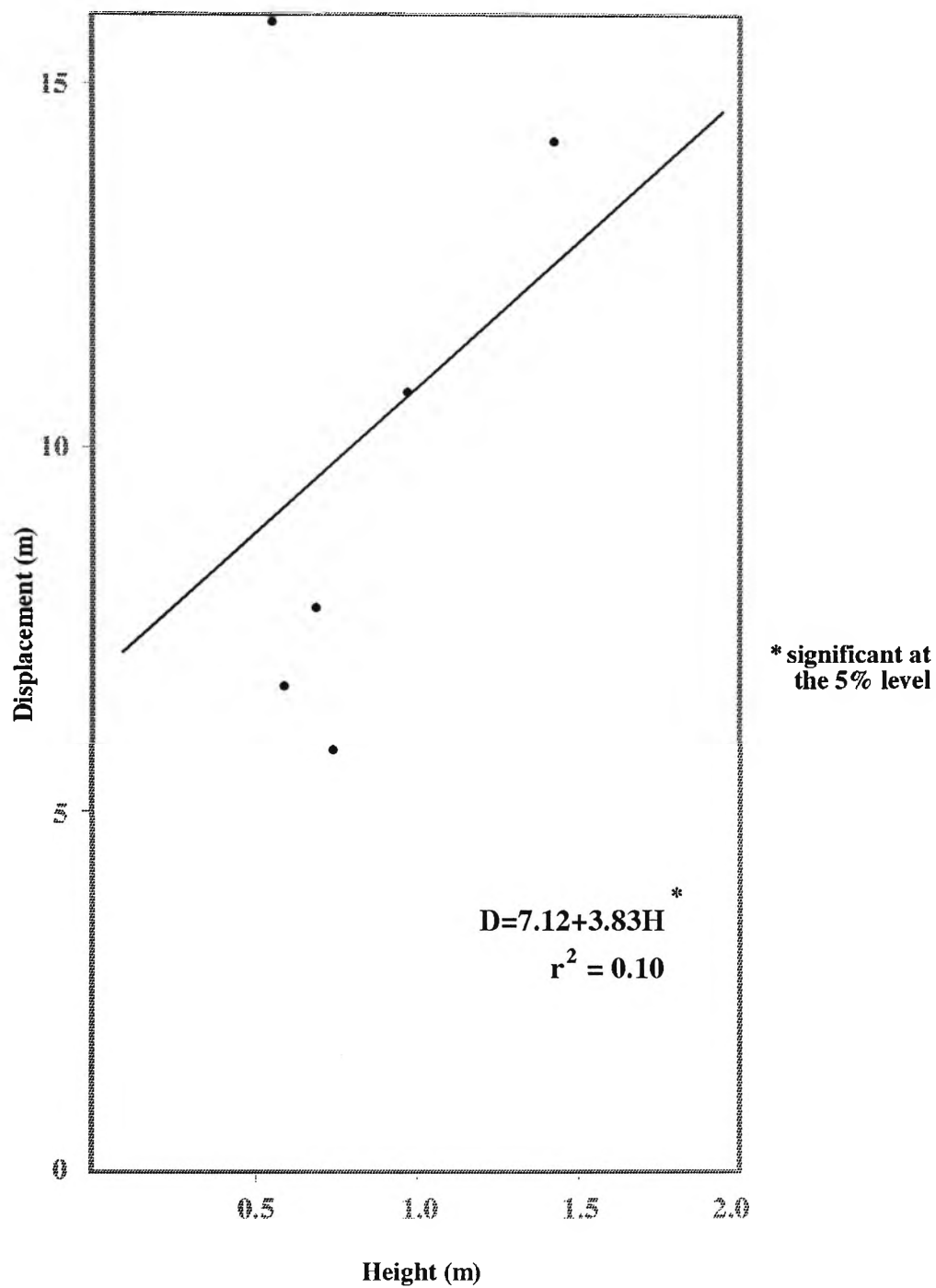
\* significant at the 5% level

**Figure 5.3 Dune height and displacement, forward direction, based on slipface height (Walvis Bay and Swakopmund dunes)**



\* significant at the 5% level

**Figure 5.4 Dune height and displacement, forward movement only, based on dune centre-point calculation Walvis Bay and Swakopmund**



**Figure 5.5 Mean height of each dune graphed against total displacement in a consistent direction (Walvis Bay and Swakopmund dunes)**



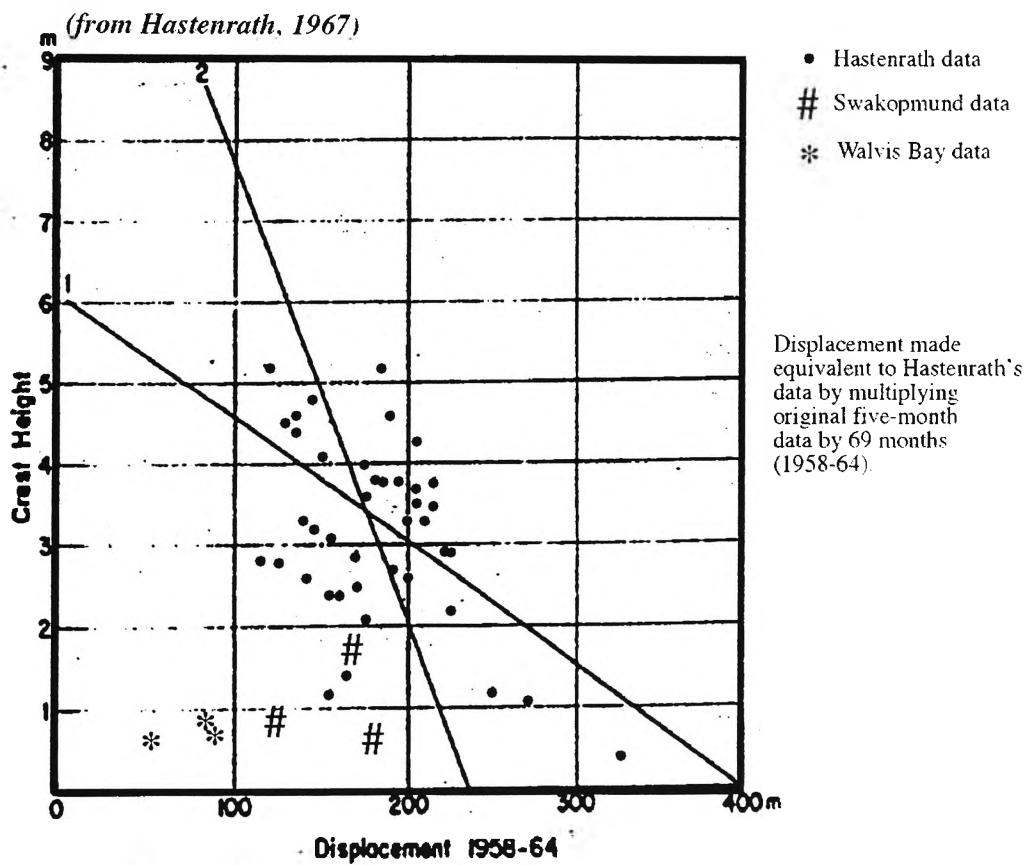
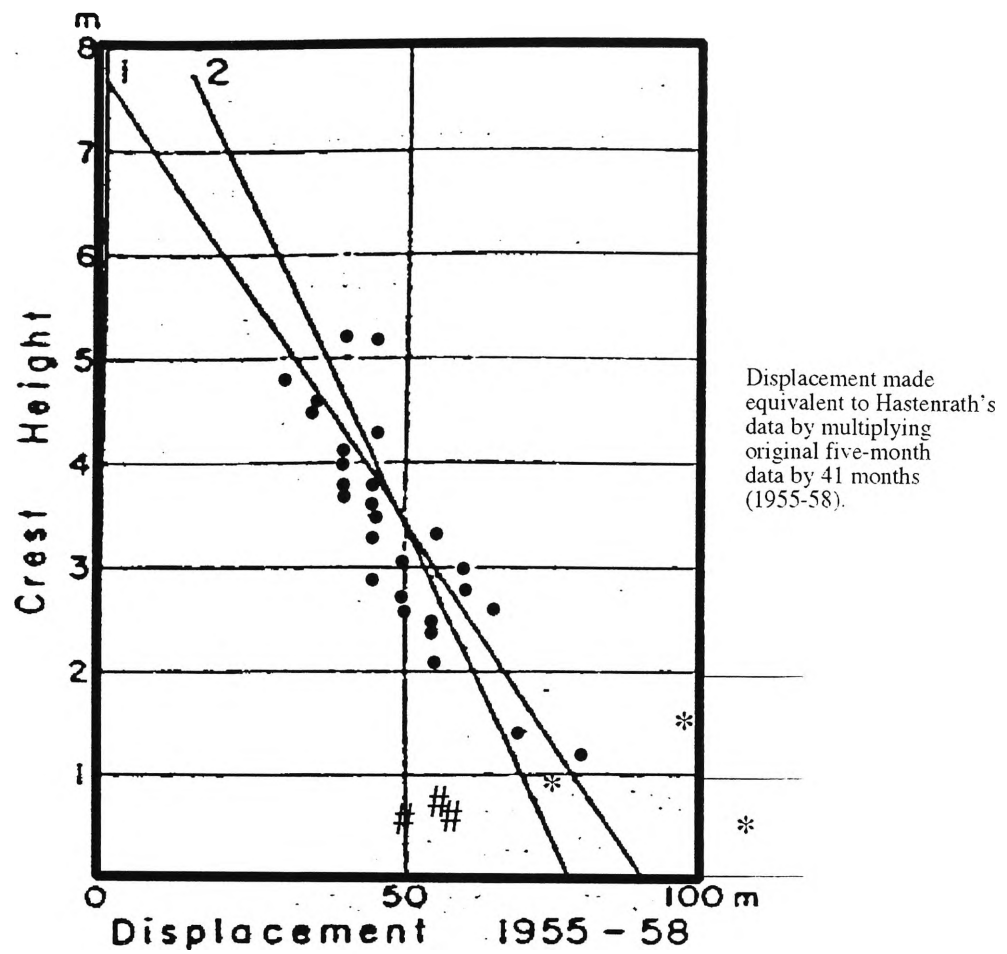
dunes must be manifested in dune morphology. Further details on the possible relationships between dune shape and dune height are included in section 5.5.

### 5.2.1 A Comparison Between Walvis Bay/Swakopmund Dunes and Previous Morphometric Studies

Hastenrath (1967) plotted the heights of 42 dunes against their displacement for the period 1955-58 (41 months), and again for the period 1958-64 (69 months). As a comparison, both the Walvis Bay and Swakopmund data were plotted against his data (Fig. 5.6). Prior to plotting, Hastenrath's displacement values (x-axis) for 41 and 69 months were adjusted to six monthly time periods to allow a proper comparison to be made. An average rate of displacement and dune height for each of the six dunes was plotted on Hastenrath's graphs. The Namib values as a whole appear to plot poorly on the 1955-58 graph; except for WB1, the Walvis Bay and Swakopmund average dune heights are less than one metre, while Hastenrath's dunes are all much higher. The corresponding displacement is lower overall, with the Swakopmund dunes showing the lowest crest heights and net displacement of all six dunes.

The 69-month graph (1958-64) again shows the Walvis Bay and Swakopmund dunes exhibiting lower overall crest heights and displacement rates. Over this time period, the values deviate significantly from the trend line, except for WB1. Swakopmund particularly has the lowest heights and the lowest displacement rates of all the dunes. Similarly, the Namib data did not fall within the range of Khalaf and Al-Ajmi (1993) 8-month survey data either.

Finkel (1959) also plotted a relationship between slipface height and displacement over a 3-year period (36 months) (Fig. 5.7). As with Hastenrath's data, the time period of the displacement (y-axis) was made equivalent to six months prior to plotting the Namib data.



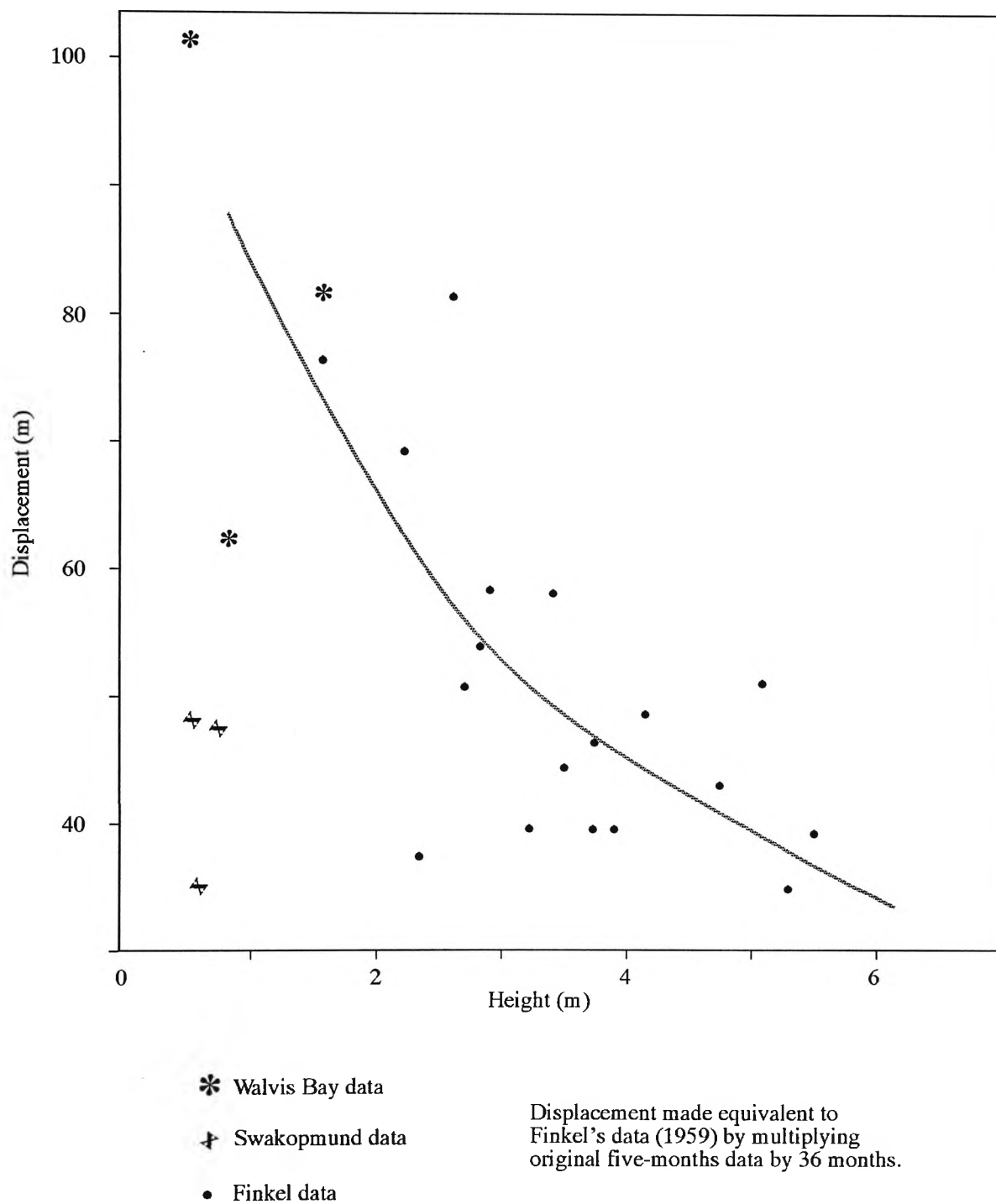
**Figure 5.6 Dune height and displacement for both the Namib dunes and Hastenrath's dunes**

This was done by plotting the five-month average height of each of the six dunes against the corresponding mean dune displacement. The displacement values were extrapolated to Finkel's 36-month measurement period. Of the six dunes, only those from the Walvis Bay study area plot within Finkel's existing data points. Swakopmund dunes fall well away from the trend line.

Long and Sharp (1964) measured height and displacement of dunes in Salton Sea over a period of seven years, from 1956-63. The Namib data also falls well away from Long and Sharp's dunes data curve, and are not shown here.

In general, the Walvis Bay and Swakopmund data do not plot particularly well on any of the graphs. These comparisons indicate that as the time between measurement is increased, the overall fit of the Namib data is reduced. Long and Sharp's figure (84 months) supports this, as the Namib data was unable to be accurately plotted on their graph. The Walvis Bay data plot reasonably well on Finkel's graph (36 months). These results may indicate that in addition to time, dune shape may be a determinant in the height and displacement relationship. The Walvis Bay dunes exhibit a closer approximation of barchan morphology compared to the Swakopmund dunes. They also show a stronger relationship between height and displacement than the Swakopmund dunes.

The error resulting from making five-month displacement/height data comparable to the same data obtained over longer periods may influence the results. The extrapolation in all cases assumes a constant rate of displacement. It also assumes displacement in a consistent direction. It has been demonstrated in Chapter Four that the Namib dunes migrated in various directions over the five-month period, resulting in a higher measurement of displacement than would have been measured by the previous studies, which used two measurements separated by several years as a measure of displacement. Because of the length of time between



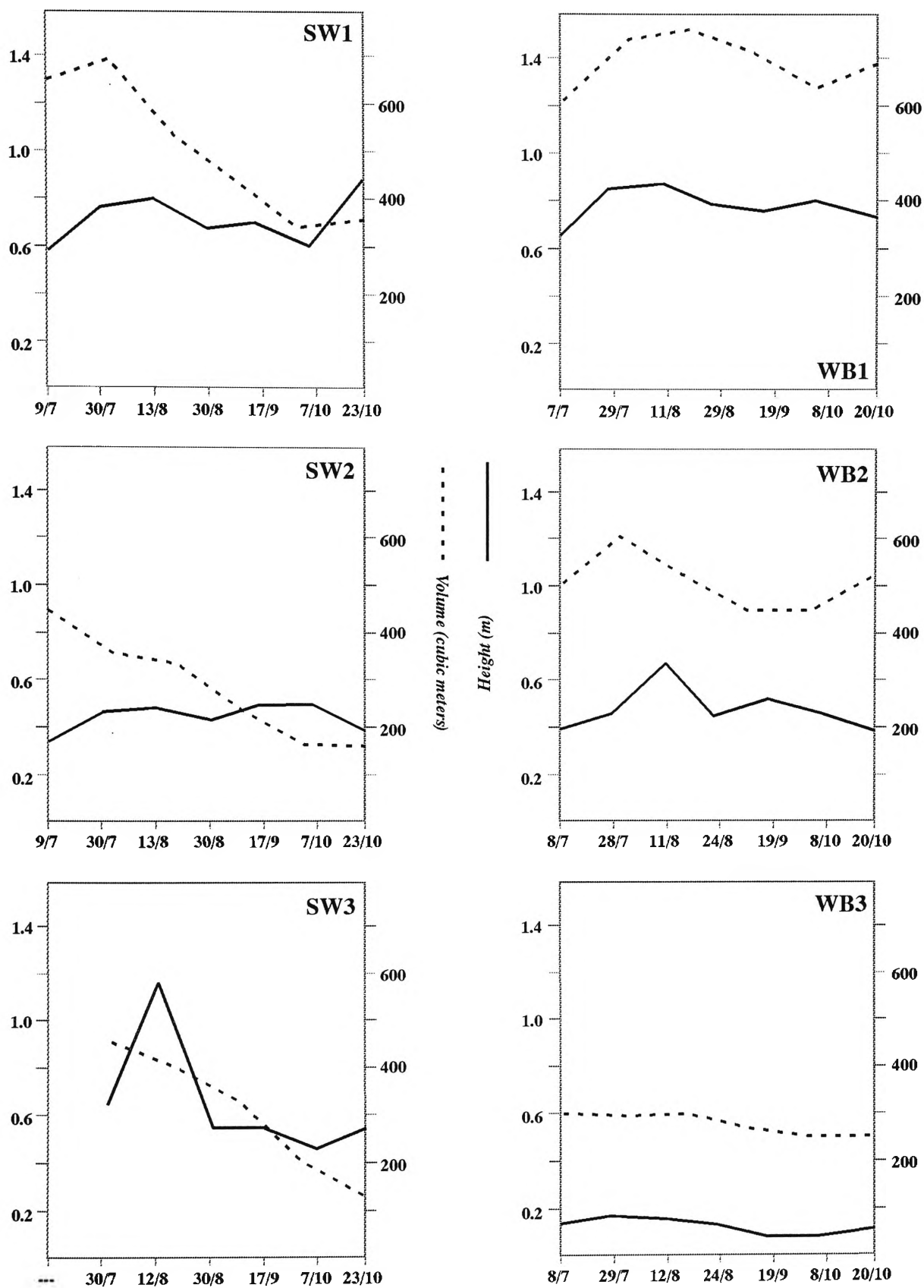
**Figure 5.7 Dune height and displacement data for the Namib dunes and for Finkel's dunes.**

displacement measurements, any non-forward movement (which constitutes a portion of total displacement) would not have been accounted for in these studies, implying that a comparison with the Namib data may not provide accurate results.

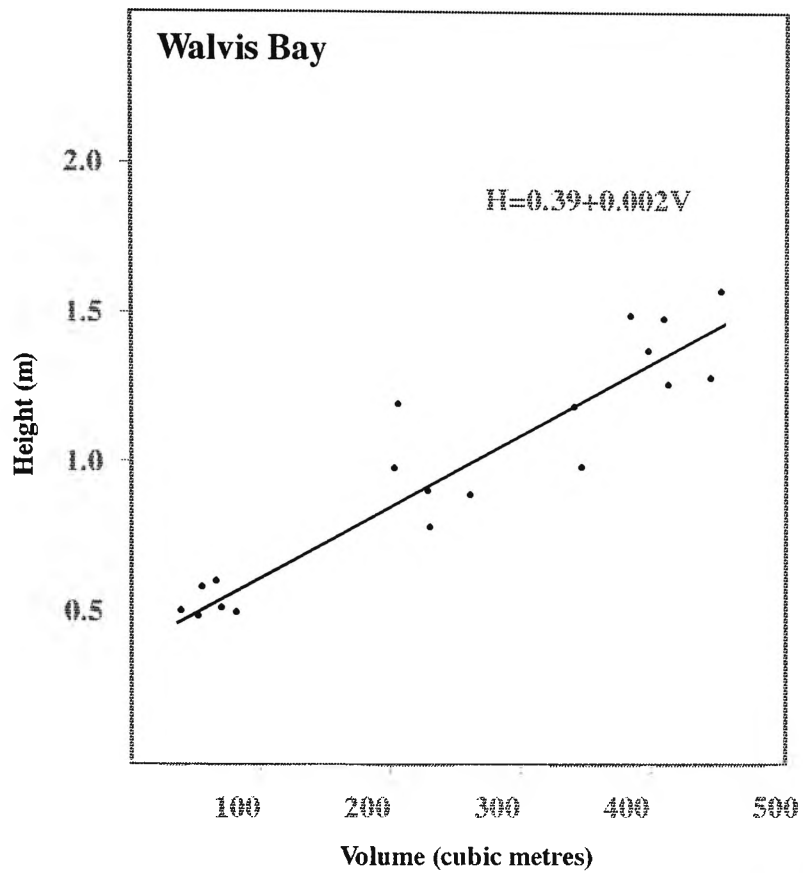
### 5.3 DUNE VOLUME vs. HEIGHT

Figure 5.8 illustrates a graphic (non-statistical) representation of the relationship between dune volume and dune height for the Namib dunes. Interestingly, the Walvis Bay dunes show a better correlation between volume and height than do the Swakopmund dunes. An overall trend of decreasing height is apparent in the Swakopmund dunes; however, corresponding values for volume do not exhibit a similar trend. For Walvis Bay, the changes in height strongly parallel the changes in volume. As the graphs (Fig. 5.8) illustrate, a strong trend is apparent, particularly for the Walvis Bay dunes. As volume increases, there is a corresponding increase in dune height. Why this relationship is not as significant for Swakopmund is not immediately apparent.

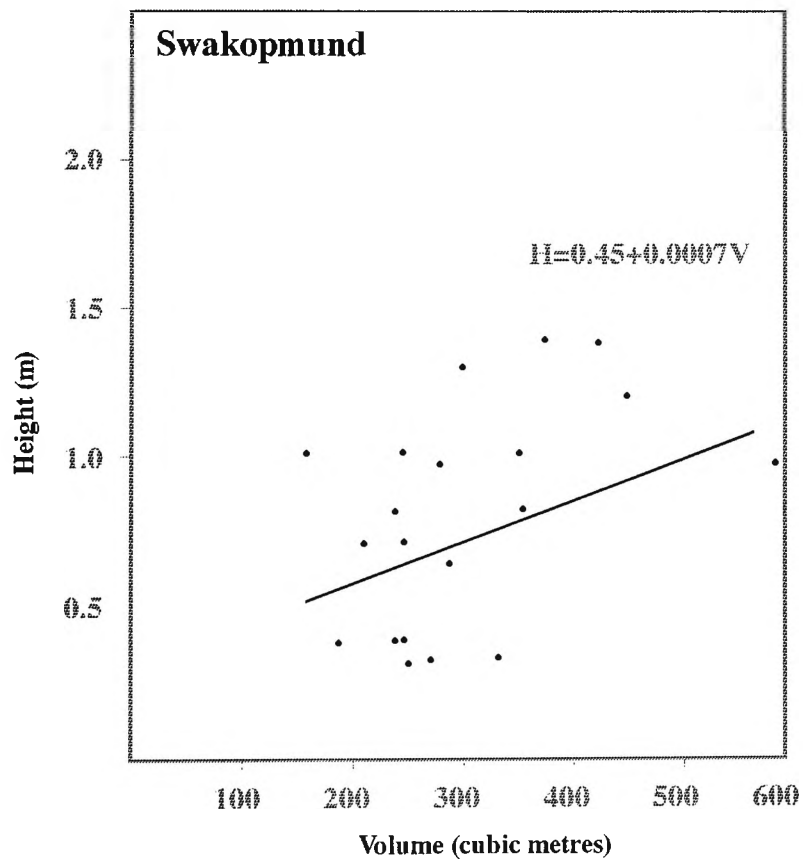
To statistically test this relationship, volume was plotted against height for both the Swakopmund dunes and the Walvis Bay dunes. It was hypothesized that as dune volume increased height would show a corresponding increase. Figure 5.9 shows the results of the graphed data and the associated statistics and regression equation. For the pooled data, a high level of correlation is indicated by the t-statistic of 3.26, which is significant at the 1% level (Table 5.2). Individually, the Walvis Bay dunes showed a significantly stronger correlation between the variables than the Swakopmund dunes, a result possibly attributable to their more barchanoidal shape. The statistical analysis also revealed that the Walvis Bay dune heights were higher on average than those of the Swakopmund dunes. However, volume for the Swakopmund dunes was higher overall than for Walvis Bay. These observations suggest that



**Figure 5.8** Graphs depicting non-statistical relationship between dune volume and height, Namib dunes



(a)



(b)

**Figure 5.9** Graphs depicting the statistical relationship between dune volume and height, Namib dunes

the Swakopmund dunes are bigger in actual size, based on calculated volume. Dune heights do not exhibit a corresponding increase, indicating the dunes must have a flatter overall shape.

The regression of volume on height also proved to be significant (Fig. 5.10). Based on these two regressions, it was hypothesized that there is a feedback effect between dune height and volume in Walvis Bay.

To test this hypothesis, the Granger test of causality was employed (Granger, 1969). This test shows conclusively that a bi-directional effect exists between dune volume and height in Walvis Bay, by disproving the following null hypotheses:

$H_{01}$  = volume does not cause height  
(rejected at the 1% level of significance)

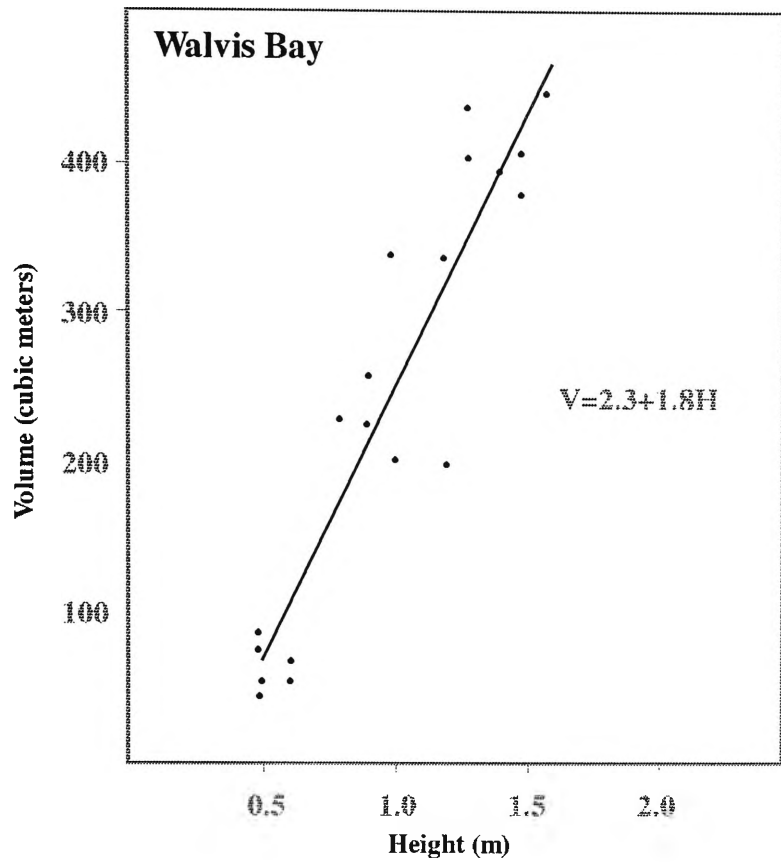
$H_{02}$  = height does not cause volume  
(rejected at the 10% level of significance)

The Swakopmund dunes were not tested for feedback, based on the results of the original regression, which indicated no relationship existed between height and volume.

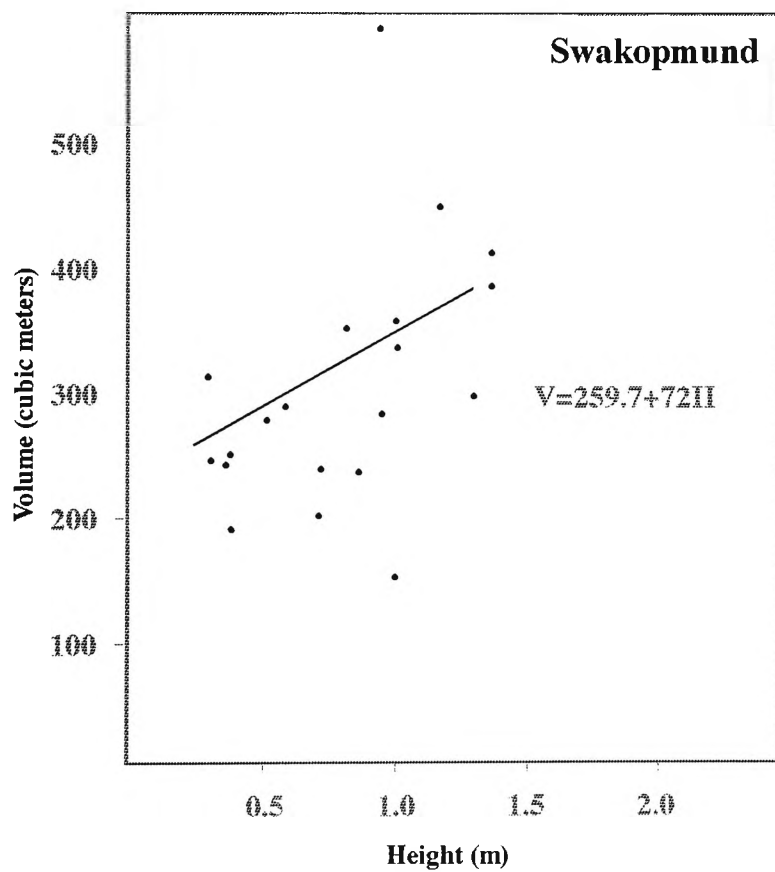
#### 5.4 DUNE VOLUME vs. DISPLACEMENT

The Walvis Bay and Swakopmund data were plotted separately to assess the relationship between dune volume and displacement (Fig. 5.11). It was hypothesized that an increase in volume would result in a decrease in displacement, since past research discussed in Chapter Two has shown that as dune height (and hence volume) increases, dune displacement decreases. A regression analysis was performed on the Walvis Bay and Swakopmund data.





(a)



(b)

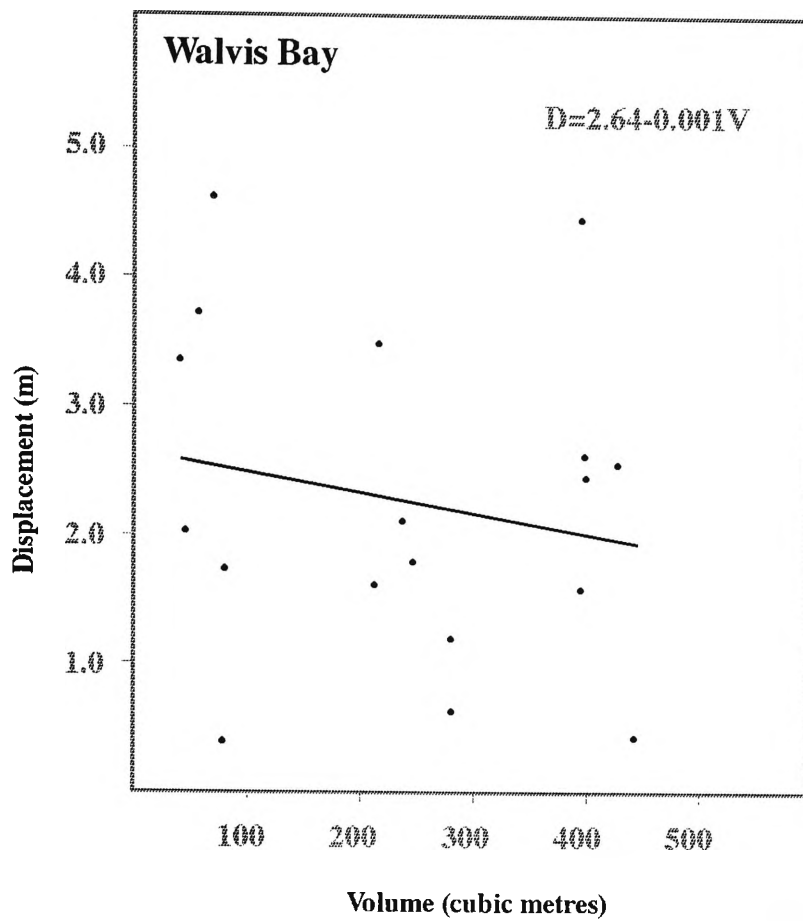
**Figure 5.10** Graphs depicting the statistical relationship between dune height and volume, with height as the dependent variable (Namib dunes)

Results indicated there was no significant relationship, although Walvis Bay appeared to exhibit a very slightly stronger correlation, based on the  $r^2$  value.

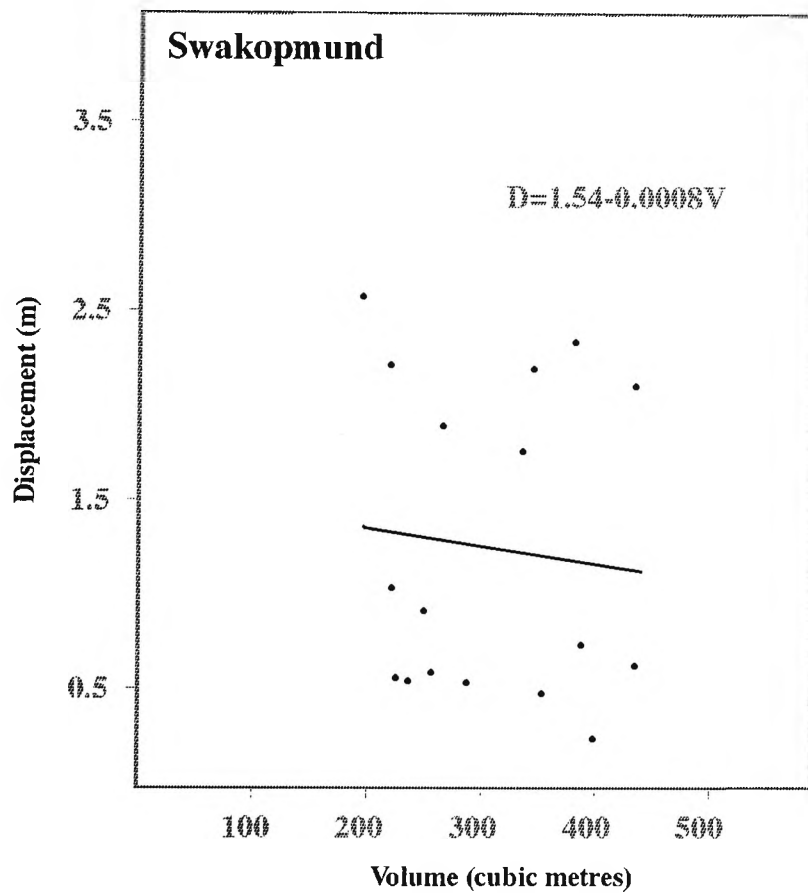
The data were then pooled and regression performed on this larger data set. As with the results from the previous test, no significant relationship between the variables was established at the 5% level. It was reported in Chapter 4 that a slight (non-statistical) correlation between volume and displacement was observed. These results were based on the graph of volume change (Fig. 4.8b) against displacement, which show a slight negative relationship between dune volume and displacement. The statistical test of this relationship presented here shows that this relationship is not statistically significant.

Obviously, the relationship between dune displacement and volume is not exclusive of variations in wind velocity and direction, as well as sand supply. The highest amount of displacement for all dunes, with the exception of SW1 and SW2, occurred between Survey 1 and Survey 2. This was also the time of the strong easterly wind storm of 21 July. These easterly winds were actually very strong for several days prior to the record winds of 21 July, as determined from wind data for July. The amount of dune movement may be explained by the velocity and direction of these winds. As the wind direction switched from southwesterly to easterly, the dune reversed correspondingly, resulting in a relatively high degree of displacement. The fact that the volume did not change significantly is most likely attributable to the continued availability of an upwind sand supply.

Norris (1966) examined correlations between volume changes and rates of movement of barchans. His findings indicated that over the short-term (one month) there was little or no correlation between volume and movement. However, over longer periods a relationship existed. An explanation is possibly a lag or delayed response in movement exists due to changes in wind strength. This means that increased displacement of the dune occurs without



(a)



(b)

**Figure 5.11 Dune volume and displacement, Namib dunes**

an immediately apparent change in volume. Norris (1966) considered that changes in sediment supply, due to periodic flooding of stream channels, may have explained the variations in volume.

The lack of a significant relationship between volume and movement in the Walvis Bay dunes may be both due to the short time period between surveys, combined with variations in sand supply and wind intensity. In the Namib, the easterly winds tend to be low frequency/high intensity events, with the moderate southwesterly winds predominating. The Kuiseb River delta, adjacent to the Walvis Bay dunes, floods periodically, depositing sediment along the marginal banks. During southwesterly winds, this sediment may be blown into the dunefield, a process observed over the study period.

Migration patterns for the Swakopmund dunes follow similar trends to the Walvis Bay dunes but distances are significantly less. At best, the data for Walvis Bay indicate that for individual dunes, volumes do not vary significantly, but the corresponding displacement values vary considerably. Swakopmund dunes show even less of a relationship, with displacement and volume showing little variation.

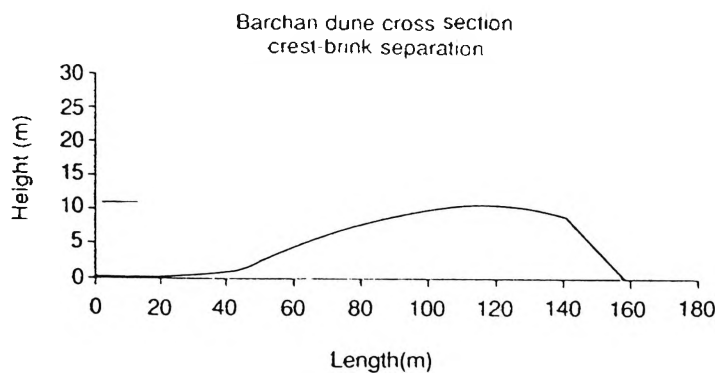
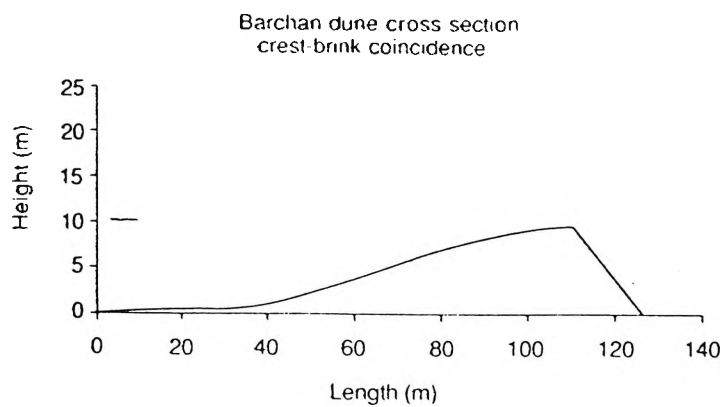
## 5.5 THE INFLUENCE OF DUNE SHAPE ON THE RELATIONSHIP BETWEEN HEIGHT, VOLUME AND DISPLACEMENT.

Hastenrath (1967) observed that dune shape changes with dune size; as crest height diminishes, the angle between the windward slope and the desert surface decreases, and the barchan becomes flatter overall. It is not made clear in Hastenrath's study whether size, as a function of mass (or volume), actually decreased or increased with the change in height. The implication of this observation, i.e. that dune height decreased and the dune became flatter, is that mass, and therefore size, is maintained. Petrov (1976) alludes to the importance of size

determination when studying dune movement. Height is universally used in these cases, and often justifiably so. However, Petrov states that it is unfortunate that the literature does not contain information on size, implying that these data are important in the calculation of true dune size.

The two profiles shown in Figure 5.12 illustrate how dune length can increase while height remains relatively constant. These changes are accompanied by changes in dune shape, as the slipface position varies. These shape changes may also be a function of wind velocity and sand supply. According to Howard et al. (1977) when there is little incoming sand, the windward slope of a barchan is steeper and there is flow divergence around the dune sides. Conversely, with a strong supply of incoming sand (and higher wind velocity) the dune elongates parallel to the direction of the wind.

Differences in slipface height and dune height were discussed in section 5.2. It is apparent from Figure 5.12 that slipface height may not represent the highest point of the dune, as is the case with the Namib dunes. The degree of variation in the coincidence of slipface height and dune height is often taken as an indication of dune maturity (Cooke et al., 1993). As dune (crest) height approaches the slipface (brink) height, a dune is seen to be more mature (or in 'equilibrium') than one where crest/brink heights are significantly different. These differences can be seen in the Namib dunes, where the level of crest/brink separation is greater for the Swakopmund dunes than for those in the Walvis Bay study area. Coincidentally, the Walvis Bay dunes also exhibit a more barchanoidal form than do the Swakopmund dunes. These morphologic differences may indicate that the Swakopmund dunes are less 'mature' than the Walvis Bay dunes, particularly when the evolutionary relationship of these dune types is considered.



**Neighbouring crest-brink separated and crest-brink coincident dunes in the Sultanate of Oman in July 1990**  
(in Cooke *et al.*, 1993, courtesy of Wiggs, 1993).

**Figure 5.12 Dune profiles showing crest-brink separation and crest-brink coincidence**

## 5.6 CONCLUSION

The Namib dunes do not exhibit strong relationships between dune height, volume, and displacement, nor do they, coincidentally, exhibit a symmetrical shape. The only variable exhibiting a significant relationship is that between volume and height, but only for the Walvis Bay dunes. The higher volume, and hence greater size, of the Swakopmund dunes was not accompanied by an increase in height measurements. This implies lateral increases in dune size or length are not accounted for by the two-dimensional height measurement used most frequently as an indicator of size.

The shape of the Namib dunes is not defineable by accepted criteria (see Chapter 2) for a significant portion of the survey period, the exception being the Walvis Bay dunes, which exhibit asymmetrical barchan morphology towards the end of the survey period. It may therefore not be valid to assume that relationships based on previously studied barchans of symmetrical (or 'classic') shape should be comparable to the Namib dunes. This partially explains why the results for height/displacement relationships calculated for the Namib dunes, particularly Swakopmund, do not correspond with results of previous studies.

The inconsistencies in the Namib results and their comparison with previously collected data indicate that other factors must play a significant role in dune displacement, since the statistical results for the Namib dunes indicate a poor correlation between height and displacement. Despite the fact that the majority of the studies (see section 5.1) of barchans indicate a strong correlation between movement and height, inconsistent results were found in this study. This lack of relationship between dune height and displacement, and volume and displacement, may be due to a number of factors:

(1) This study is short-term (six months), compared to the other studies. This thesis presents six observations for six dunes over a six-month period, whereas the above studies, specifically Finkel and Hastenrath, present one or two observations of many dunes over several years. The differences in <sup>time</sup>scale may explain some inconsistencies when comparing results. However, Khalaf and Al-Ajmi (1993) conducted a similar type of study to that presented in this thesis, over a comparable time period, and found that height and displacement showed a high level of correlation ( $r = 0.85$ ). These dunes were symmetrical in shape, and ranged in height from 1.8m - 7m. The results of this study imply that <sup>time</sup>scale may not be the controlling variable in the dune height/displacement relationship, and that dune shape may be a more significant factor. As a dune approaches the 'classic' barchan shape, the relationship between dune height and displacement may become more significant.

(2) The number of observations for the Walvis Bay/Swakopmund study was low, compared to the other studies. This small sample size may have contributed to the poor correlations, although Khalaf and Al-Ajmi (1993) had a sample size of 10 dunes, indicating that a small sample size may not be the significant factor in the discrepancy between height and displacement.

(3) Some discrepancies in results may be explained by the way the dependent variable (height) was determined. Hastenrath used the rate of displacement as the dependent variable, whereas the other studies used actual displacement as the dependent variable. In addition, actual movement should take into account not only forward movement, but displacement in other directions resulting from variations in wind direction.

In the case of the Namib dunes, using dune height in preference to slipface height may reduce the comparability of this data with previous studies which used slipface height exclusively in their study of dune height/displacement relationships. This is particularly true for the



Swakopmund dunes, where slipface height was almost half dune height. However, the statistical analysis indicated that the results of the Namib dune height/displacement study yielded similar results when either dune height or slipface height was used.

(4) All studies concede that variations in dune displacement may be attributed to a variety of factors, such as dune shape, volume, sand supply, topography, wind conditions and grain size. The general conclusion is that the nature of this relationship is dependent on local wind fields and their degree of variability (see Chapter 4).

Norris (1965) observed that little or no correlation between volume change and rate of movement occurred over short periods. However, others believe shifts in wind conditions may lead to significant shifts in displacement direction, and that only short-term studies would be able to measure these shifts (Finkel, 1959). Long-term studies do not adequately account for possible non-forward movement, and subsequently may not present an accurate measure of overall displacement.

The size of the dunefield and placement of the dunes within the dunefield may also explain differences in displacement rates. The dunes in the Walvis Bay dunefield are relatively isolated and exposed to the prevailing southwesterly winds. By contrast, the Swakopmund dunefield contains both barchan and dome dunes as well as transverse dunes, some of which provide upwind shelter from the prevailing winds for the adjacent barchans and domes, and serve as a possible sediment source in some instances.

(5) That a linear relationship does not apply for very large or very small dunes on either end of a normal distribution has been documented (Cooke et al., 1993; Finkel, 1959). A linear formula was a good predictor of dune movement for dunes 2-7m high, but performed poorly for small dunes of the order of 1m high. This finding in part explains why the Namib dunes

would not be expected to display a statistically significant relationship between height, volume, and displacement, as the greatest height attained during the survey period was 1.6m (WB1), which is on the lower end of the size scale.

(6) In Chapter 4, dune volume and displacement relationships were examined. The results presented in this chapter are in agreement with those in Chapter 4. Although the statistical relationship between these variables is weak, it still indicates that an increase in volume results in a decrease in displacement. The results presented in Chapter 4, which compare the change in volume to displacement, may therefore be accepted as true. However, subsequent to the statistical analysis, the results are not as significant as previously believed.

Volume and height showed a high degree of correlation for the Walvis Bay dunes. By contrast, the Swakopmund dunes showed little correlation between these variables. Overall volume calculations for the Swakopmund dunes are greater compared to Walvis Bay, but heights are less. The discrepancy in these results indicate that shape may influence the relationship between height and volume. Dune shape is distinctively different for the dunes in each study area. These results imply that as a dune approaches a barchan morphology, like the Walvis Bay dunes, the relationship between volume and height becomes more significant.

(7) Since the relationships based on dune height, such as displacement/height, are largely geometric in nature (Bagnold, 1941; Lettau and Lettau, 1969; Mabbutt, 1977) they may not be totally reliable for dunes, such as the Namib dunes, which are not symmetrical, since these relationships represent two-dimensional change only. Lateral increases in size are not accounted for by height measurements, unless the dune is of a symmetrical shape.

The possible influence of shape possibly is reflected in the results of Khalaf and Al-Ajmi (1993). Their dunes were relatively symmetrical, and also showed a significant correlation

between height and displacement, despite the small sample size and comparatively short survey period.

(8) Dune height increased for WB1 and WB2 between survey period 6-7. Both dunes registered corresponding decreases in volume over this period. These results indicate that the dunes themselves were losing sediment, but dune height actually increased. This implies a redistribution of dune sediment, with perhaps a concentration near the top of the slipface where most of the height measurements were made. Dune (plan) morphology also indicates that the Walvis Bay dunes were becoming increasingly barchanoidal over the same period.

(9) The discrepancies in height and volume indicate the inherent dangers in making assumptions of dune behaviour and characteristics based on dune height alone. For all dunes except SW2 and WB3, over the period of unidirectional movement (survey 6-7), heights did not increase or decrease in conjunction with dune volume. The Swakopmund dunes (SW1 and SW3) both showed increases in volume and decreases in height; the Walvis Bay dunes (WB1 and WB2) exhibited increases in height and decreases in volume over the same period. The increase in volume is more easily explained than the decrease. Sediment can be added to the dune mass, but the overall shape can flatten, as implied by Hastenrath (1967). In the situation where dune mass (volume) decreases but height increases, the explanations are not so simple. As mentioned above, it is possible that sediment is redistributed over the dune, since shape in this case was maintained. Since these size parameters produce such different results when used as indicators of dune movement and shape, it is important to determine which is the more reliable indicator of dune size.

(10) The variation in crest/brink coincidence between Walvis Bay and Swakopmund implies that the Walvis Bay dunes, due to their greater degree of crest/brink coincidence, represent a

more advanced stage of dune evolution. This 'maturity' is further substantiated by their more barchanoidal morphology, and their greater rates of displacement.

## Chapter 6

# WIND DATA ANALYSIS

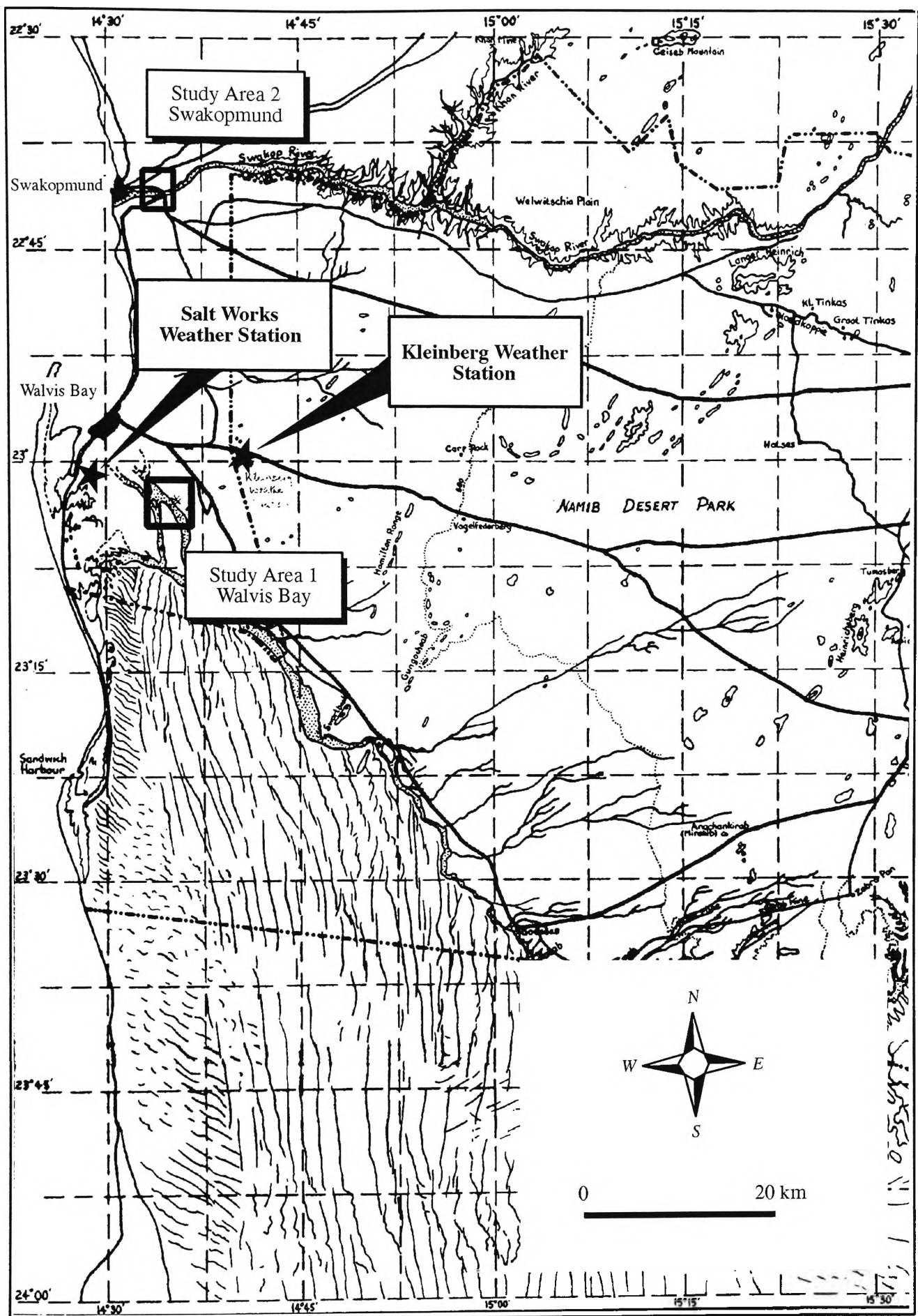
### 6.1 INTRODUCTION

It has been established that the direction and amount of dune movement is strongly related to wind velocity and direction (Bagnold, 1941; Norris, 1965; Long and Sharp, 1964; Fryberger, 1979). This chapter presents the results of an analysis of wind data in the Walvis Bay/Swakopmund region, and includes a detailed description of the two methods used to determine the wind resultants. These calculated wind resultants are then compared with inter-survey movement and direction of migration of both the Walvis Bay and Swakopmund dunes, to examine the relationship between the rate and direction of dune movement and regional wind velocities. The changes in dune morphology associated with variations in wind velocity and direction are also examined.

#### 6.1.5. The Data

The data used for the wind resultant calculations were obtained from two weather stations situated near the study areas. The Salt Works weather station is located within the coastal town of Walvis Bay, approximately 12km from the Walvis Bay study area. The Kleinberg station is located approximately 16km from the coast, and about 10km from the Walvis Bay study area (Figure 6.1). The Swakopmund site is located approximately 38km from the Kleinberg weather station and 35km from Salt Works.

Wind data was not continually available from either site for an entire survey period. For the months of August and September, the raw wind data from the Salt Works weather station were provided by the C.S.I.R. in the form of tables with velocities and directions (in degrees) over



**Figure 6.1 Location of Kleinberg and Salt Works weather stations**

24-hour periods. For the months of July and October, the Kleinberg chart records of wind data were provided by D.E.R.U., and directions and velocities were determined using a nomograph. Data from both weather stations were available for part of August and October; in these instances, the data from both stations were employed.

The data were divided into corresponding inter-survey periods, for a more accurate comparison with the dune movement between surveys. Depending on the completeness of the data set, either Salt Works or Kleinberg data were used.

## 6.2 METHODOLOGY

Two methods were employed to determine wind resultants in the study region; the Landsberg-Jennings (henceforth referred to as LJ) method, and the Fryberger-Dean (FD) method. Both methods are designed to calculate resultant wind direction, given basic wind velocity and direction data. In addition, the FD method also allows the computation of the directional variability of the wind and provides a wind regime classification system based on drift potential. Details of both these analytical methods are found in the following sections.

### 6.2.1. The Landsberg-Jennings (LJ) Method

This method requires wind velocity data (m/sec) and direction (eight or 16 quadrants) for use as input data in the calculation of the wind resultant direction. Wind velocities are grouped into arbitrary classes, from 4 m/sec (threshold wind velocity) to 20 m/sec, and their respective directions noted. Sixteen directional quadrants were used in this case. It is understood that higher velocity winds will have an inherently greater effect on overall sediment transport. Accordingly, each velocity class contains a weighting factor derived from average class velocities, that is applied to each observation within that class. This procedure was followed for

all subsequent wind data sets, and a wind resultant diagram was then constructed for each survey period (Fig. 6. 2).

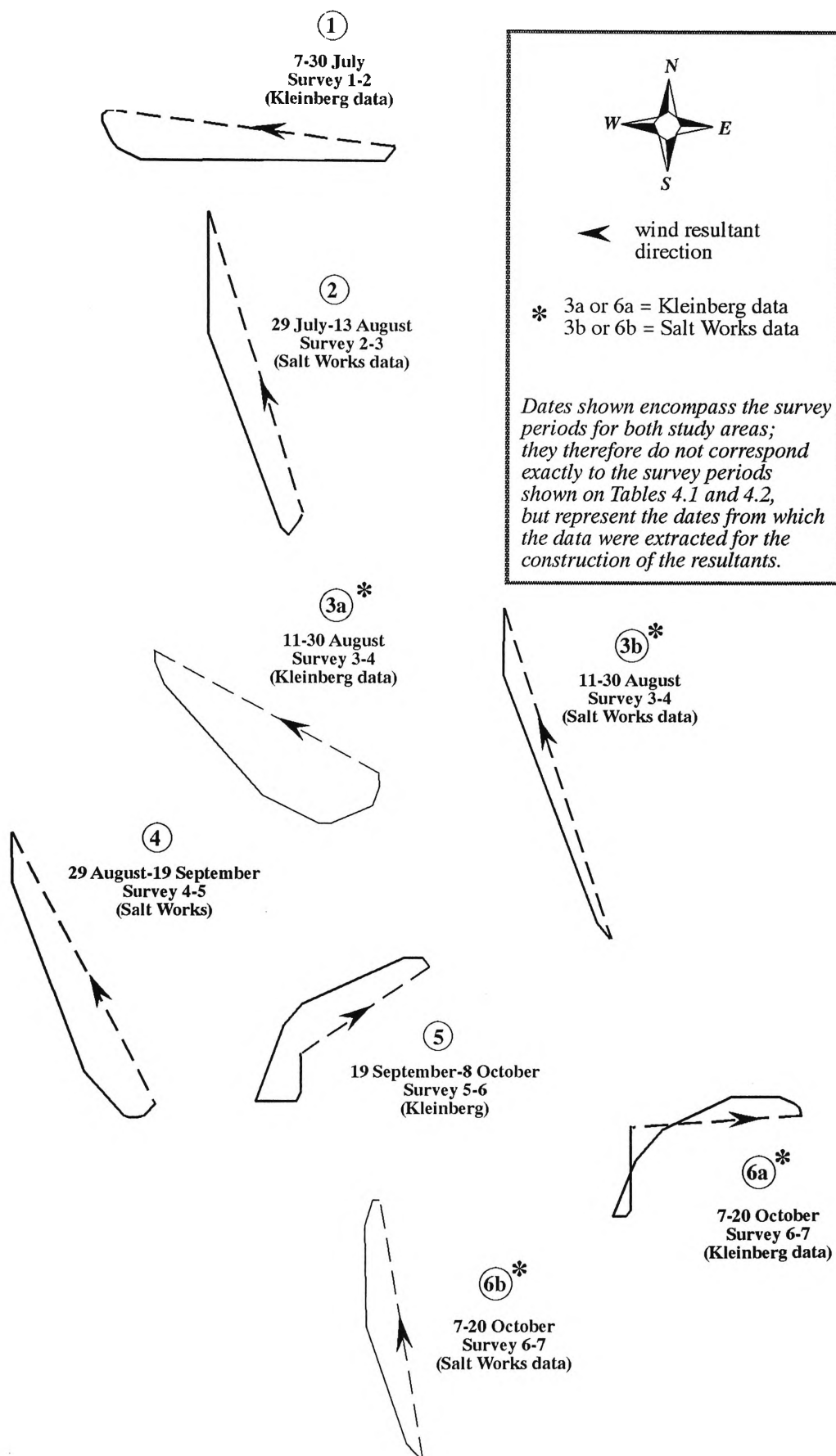
#### 6.2.2. The Fryberger-Dean (FD) Method

This method presents an alternative to the LJ method. In addition, it also represents a more sophisticated analysis of the wind data using what are essentially identical data input parameters to those used in the LJ method. Due to the complexity of this method, a worked example has been included in Appendix II. A brief description of the method is outlined below.

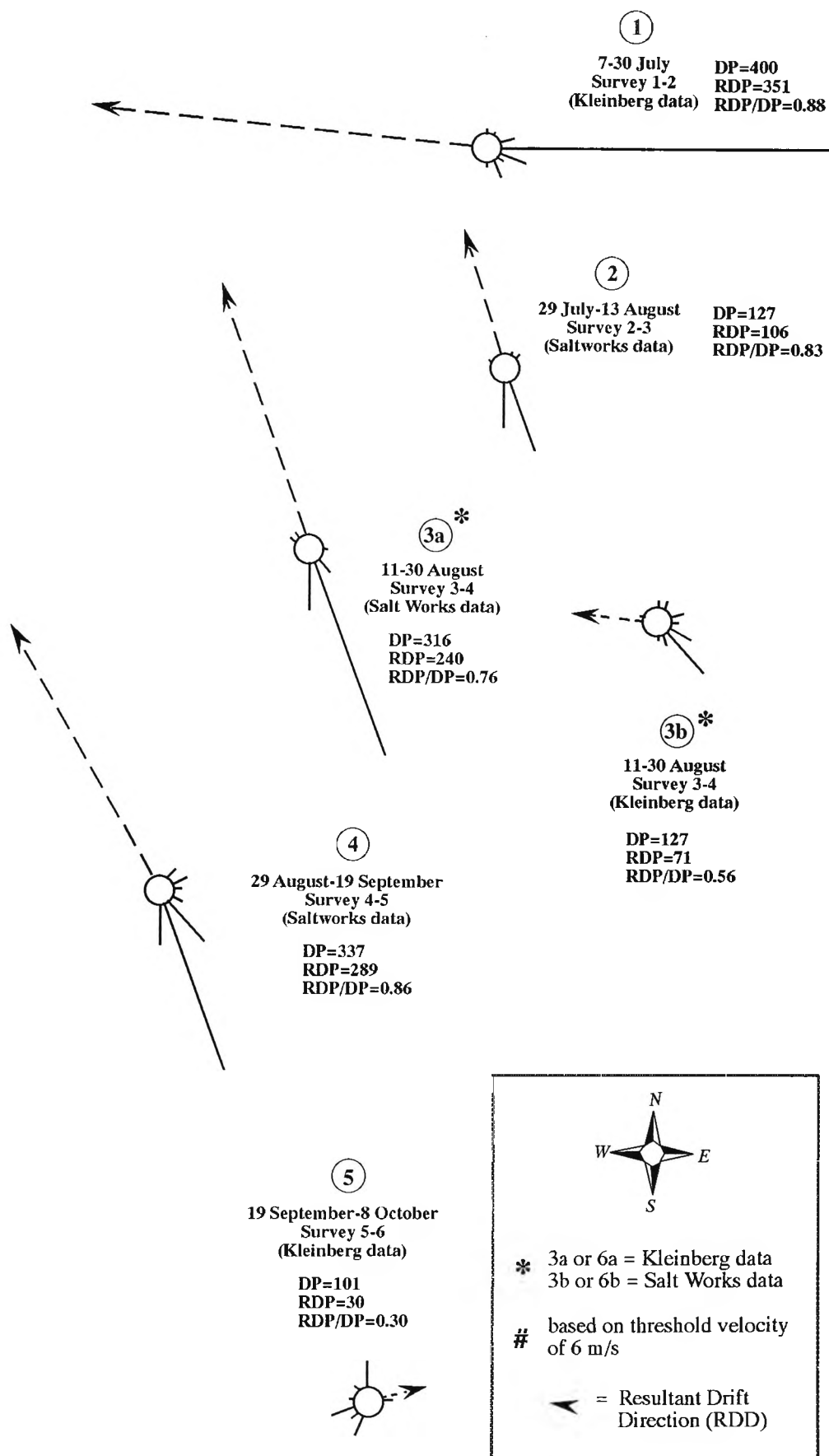
As with the LJ method, the FD method uses wind velocity and direction data and applies a weighting factor derived from mean wind velocities within the velocity classes, and impact threshold wind velocity (4 m/sec). The percentage occurrence of wind in each of the 16 velocity classes is multiplied by the appropriate weighting factor (see worked example, Appendix II). The results of this calculation are given as vector units for each velocity class, which are then totalled to give a drift potential (DP) and plotted as a sand rose. The sand rose represents potential sand drift from the 16 directions of the compass. The arms of the sand rose are proportional in length to the potential sand drift from a given direction as computed in vector units (Fryberger, 1979). These sand roses are shown in Figure 6.3.

The resultant drift direction (RDD) is also shown on the sand roses. The RDD expresses the net direction sand would drift under the given wind directions. The magnitude of this drift is the RDP (resultant drift potential), shown in vector units. This value is determined by multiplying the drift potential (DP) by the sin and cosine of each of the 16 compass directions used in previous calculations, and expresses, in vector units, the net sand transport potential when winds from the various directions interact. The worked example in Appendix II illustrates the process whereby these values are derived.

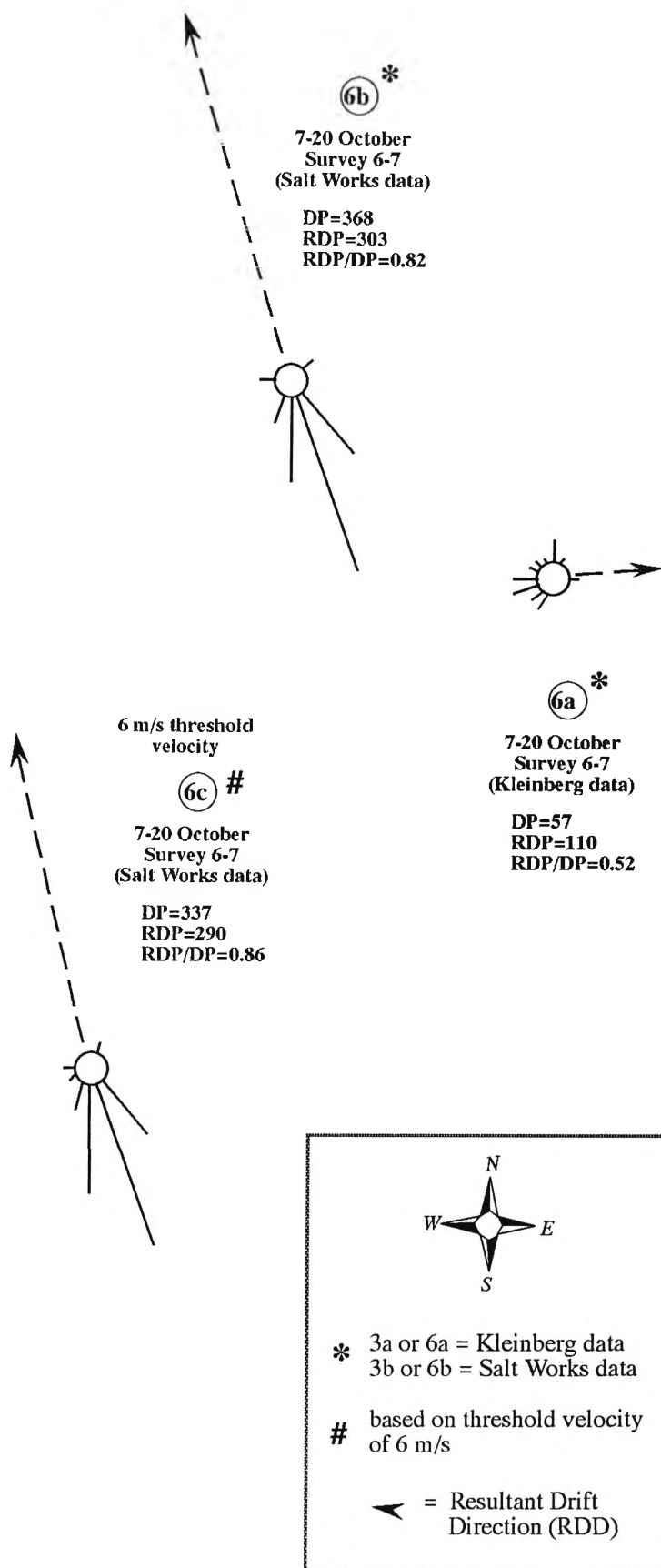




**Figure 6.2 Landsberg/Jennings (L/J) wind resultants**



**Figure 6.3 Fryberger/Dean (F/D) sand roses**



**Figure 6.3 (con't) Fryberger/Dean (F/D) sand roses**

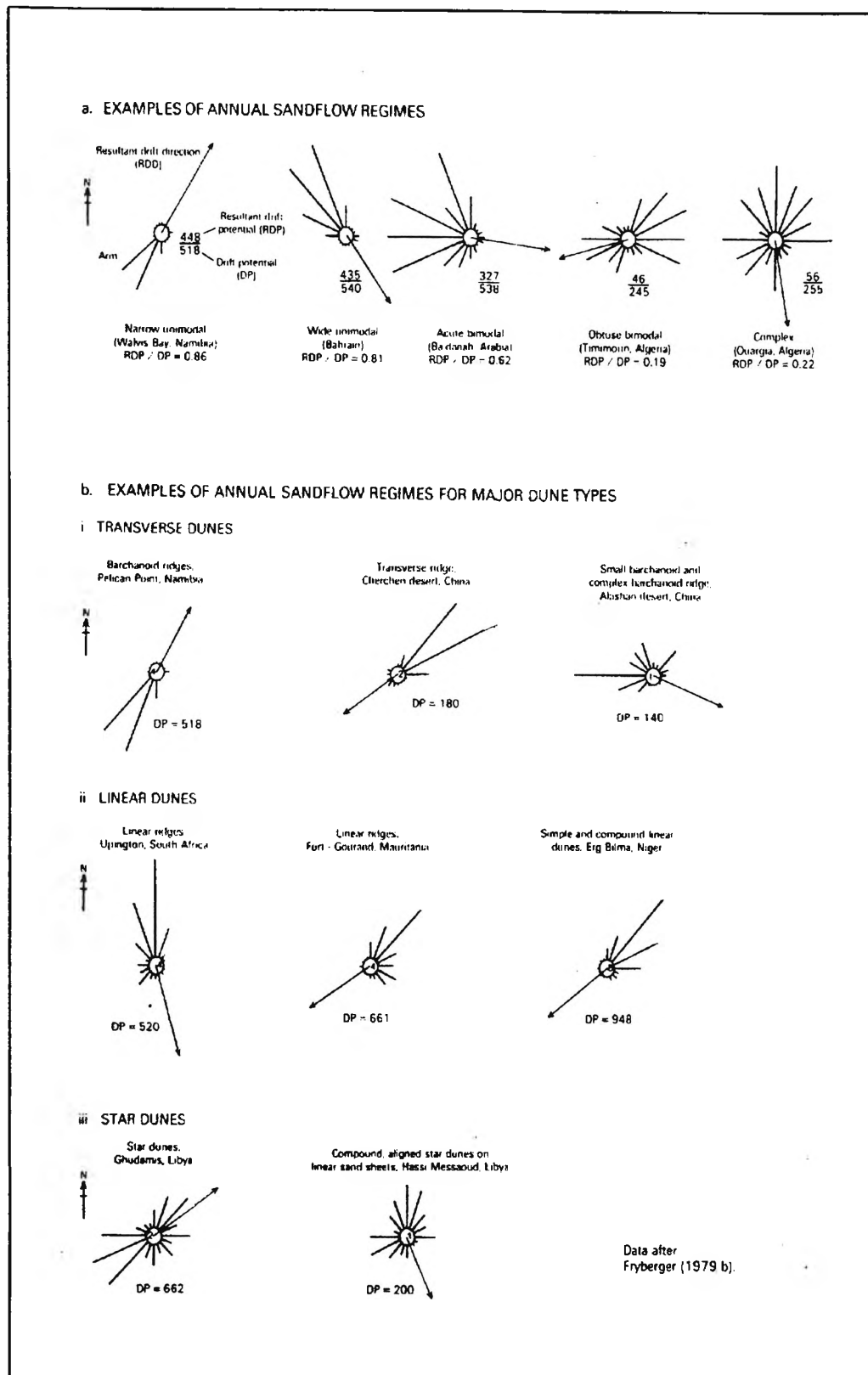
### 6.2.3 Fryberger/Dean Wind Regime Classification

In addition to the calculation of sand roses and resultant drift potentials, the FD method allows classification of wind regimes based on the drift potential of each of the sand roses. Fryberger (1979) recognizes five classes of wind types: narrow unimodal, wide unimodal, acute bimodal, obtuse bimodal, and complex. The classes are determined by the distribution peaks occurring around the sand rose and their occurrence within 16 compass directions. Only three of these classes are relevant to this study; details of these classes are found below, and illustrations of all types can be found in Figure 6.4:

1. Narrow Unimodal - > 90% of the drift potential falls within two adjacent directional categories, or within a 45° arc of the compass.
2. Wide unimodal - any other directional distribution with a single peak or mode.
3. Obtuse bimodal - a distribution of two modes, with the peak directions of the two modes forming an obtuse angle.

Associated with the directional classification is the directional variability of the wind, defined by the ratio of RDP/DP. Fryberger found that a low directional variability (0.0 to 0.3) is associated with complex and obtuse bimodal wind regimes. An intermediate value (0.3 to < 0.8) is associated with obtuse or acute bimodal winds, and a high (> 0.8) value with wide or narrow unimodal wind regimes.

The drift potential (DP), a measure of the energy of surface winds in terms of sand movement, is also associated with types of wind energy environments. Fryberger studied several desert regions and found that low-energy wind environments have a DP of <200 vector units;



Sand transport regimes represented by sand flow roses  
(after Fryberger, 1979).

**Figure 6.4 Annual sand transport regimes**

intermediate environments have a DP of 200 to 399 VU, and a high energy wind environment will have a DP of > 400 VU.

Fryberger and Dean (1979) classify the coastal areas of Namibia as being high energy, unimodal regimes. Immediately inland, they become low to moderate energy wide unimodal, and ultimately low to moderate obtuse bimodal as distance inland increases. The data in Table 6.1 indicate that the average predominant wind regime in the study area over the July-October survey period is unimodal intermediate energy. The highest drift potential occurred during July, when strong easterlies predominated.

The resultant sand flows calculated by Lancaster (1985) also indicate both seasonal and locational variability. For some southern stations during July and October, for example, directional shifts may be as much as  $180^{\circ}$ . In the northern areas, however, these directional shifts are not as marked. This variability is also found in the corresponding sand resultant data for this study, with July resultants indicating flow towards the west and northwest, and October data towards the north and northeast. In the cases where both Kleinberg and Salt Works data were used, differences in resultant drift direction occurred, specifically during the latter part of October (survey period 6 to 7). During this time, Kleinberg data indicated predominantly west to southwesterly winds, resulting in a drift direction towards the ENE. Salt Works data, by comparison, showed winds mainly from the southeast, with a resultant drift direction of NNW. During August (survey period 3-4), Kleinberg and Salt Works data were used, but the resultant drift directions were not significantly different. Both indicated a drift direction towards the NNW.

Survey	DP <sup>#</sup>	RDP/DP <sup>#</sup>	Wind Regime # Classification
* 1 - 2	400	0.88	wide unimodal
2 - 3	127	0.83	narrow unimodal
3 - 4	316	0.76	narrow unimodal
* 3 - 4	127	0.56	wide unimodal
4 - 5	337	0.86	wide unimodal
* 5 - 6	101	0.30	obtuse unimodal
* 6 - 7	103	0.57	obtuse bimodal
6 - 7	380	0.86	wide unimodal

\* Kleinberg data used in the calculation. No symbol indicates Salt Works data were used

# DP = Drift Potential  
RDP = Resultant Drift Potential

<u>RDP/DP Classification</u>		
0 - 0.3	(low)	complex, obtuse bimodal
0.3 - 0.8	(intermediate)	obtuse/acute bimodal
> 0.8	(high)	wide/narrow unimodal
<u>DP Classification</u>		
< 200	(low)	
200 - 399	(intermediate)	
> 400	(high)	

**Table 6.1 Wind regime classification, Namib dunes**

#### 6.2.4 Threshold velocity

As stated previously, threshold wind velocity is assumed to be 4 m/sec. This is the accepted velocity at which sand is moved (Bagnold, 1941; Landsberg, 1956). Fryberger, in his wind resultant calculations, used a threshold velocity of 6 m/sec.

According to Cooke et al. (1993), minimum threshold velocity decreases with particle density. Walvis Bay dunes have a mean bulk density of 2.76; Swakopmund dunes have a bulk density of 3.88, significantly higher than Walvis Bay, and which may mean that the higher threshold velocity of 6m/sec would be required in the analysis.

To determine if the 4 m/sec velocity was below effective threshold, the wind resultants for the 6-7 survey period were calculated again, using a threshold velocity of 6 m/sec, and the results compared to those calculated using the 4 m/sec threshold value. The results, based on Salt Works data only, are included in Figure 6.3. It is apparent in this example that little variation in resultant wind direction occurred when using either a threshold velocity of 4 m/sec or 6 m/sec. Since this was the case, the 4 m/sec threshold velocity was used for both the remaining LJ and FD wind resultant calculations.

### 6.3. RESULTS

#### 6.3.1 Wind Resultants

The wind resultant calculations made over the period 7 July - 23 October indicate strong easterly winds throughout the month of July, which become southeasterly over the months of August to mid-September. Southwesterly winds dominated during mid-September to mid-October. For the



remainder of the period, wind direction becomes predominantly south to SSE (Salt Works data) or southwesterly (Kleinberg data).

Tables 6.2a and 6.2b summarize the results of the wind resultant analysis. The relationship between dune displacement, RDP and DP will be examined in the following section.

### 6.3.2 The Relationship Between Displacement, Volume, and RDP

RDP (resultant drift potential) expresses the net sand transport potential when winds from the various directions interact. As such, it is expected that with a higher RDP, then sand transport and subsequent dune displacement would also be greater (Fryberger, 1979). However, inconclusive results are found when dune displacement is plotted against RDP (Fig. 6.5). Figure 6.6 plots RDP and mean displacement for Walvis Bay and Swakopmund, and includes the RDP/DP ratio. Displacement does not follow trends in RDP, except for the Walvis Bay dunes for the first two survey periods. This is the result regardless of whether Salt Works or Kleinberg data are used in the calculation.

Similar results are found when RDD (resultant drift direction) is compared with displacement direction. Again, many discrepancies exist between the calculated drift direction and measured dune displacement, exclusive of RDP or dune size. The exceptions are survey periods 1-2 and 5-6. During survey period 1-2, RDD is also towards the west, reflecting the intense easterly storm. Dune displacement for all dunes is also in the westerly direction. Dune displacement for all dunes for survey period 5-6 also coincides with the RDD.

Figures 4.9a and 4.9b (Chapter 4) illustrate dune displacement and volume. When dune displacement based on the centre-point calculation method is compared to RDP, periods of increased displacement do not coincide with higher RDP, for either the Walvis Bay or

Dune	Height (m)	Disp. (m)	Dist. bet. horns (m)	Volume (m <sup>3</sup> )	Dune form	Net dir. of move't	DP	RDD	RDP
WB1#1	1.2	4.5	16.5	337	TB	west	400*	west *	351 *
WB1#2	1.3	0.5	---	439	TB	north	127	NNW	106
WB1#3	1.6	2.6	---	447	TB	northeast	127*	west *	71 *
WB1#4	1.5	2.6	15	405	TB	northeast	337	n'west	289
WB1#5	1.4	2.5	20.5	395	TB	northeast	101*	east *	30 *
WB1#6	1.3	1.6	15	405	B	northeast	99*	east *	60 *
WB1#7	1.5		15	376	B				
WB2#1	1.0	3.5	13	201	TB	west			
WB2#2	1.1	0.6	14.5	229	TD	northeast			
WB2#3	1.3	1.2	---	341	TD	northeast	(as above)	(as above)	(as above)
WB2#4	0.9	1.8	14	226	TB	NNE			
WB2#5	0.9	2.1	15	257	TB	northeast			
WB2#6	0.9	1.6	12	226	TB	northeast			
WB2#7	1.2		11	198	B				
WB3#1	0.6	4.6	---	64	TD	west			
WB3#2	0.6	0.4	10	82	TD	south			
WB3#3	0.6	1.7	10	83	TD	northeast	(as above)	(as above)	(as above)
WB3#4	0.6	3.7	---	72	TD	NNE			
WB3#5	0.5	3.4	10	49	B	northeast			
WB3#6	0.5	2.0	7	38	B	northeast			
WB3#7	0.5		6	55	TD				

\* indicates Kleinberg data were used in the analysis

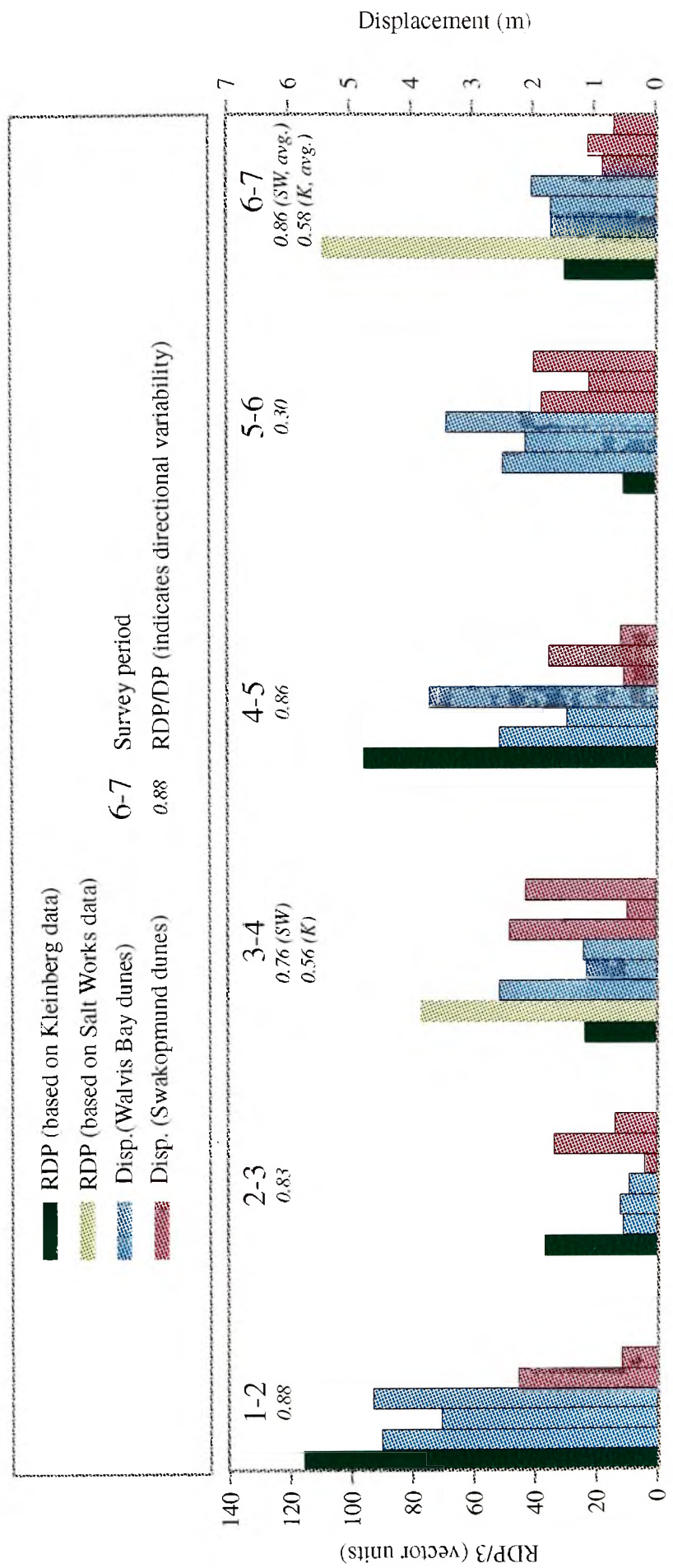
**Table 6.2a Summary of wind resultant analysis and morphometric data (Walvis Bay)**

Swakopmund dunes. In addition, the direction of dune displacement does not coincide with the RDD for most survey periods, periods 1-2 and 5-6 being the exceptions.

Volume fluctuations also do not follow RDP. Figures 4.8a and 4.8b illustrate volume change and displacement. When these changes are compared to RDP (Fig. 6.3), it is apparent that a greater RDP, such as for survey periods 1-2 and 6-7, does not result in a consistent change in volume. For these periods, volume for some dunes increases while decreasing for others. These discrepancies occur irregardless of dune size.

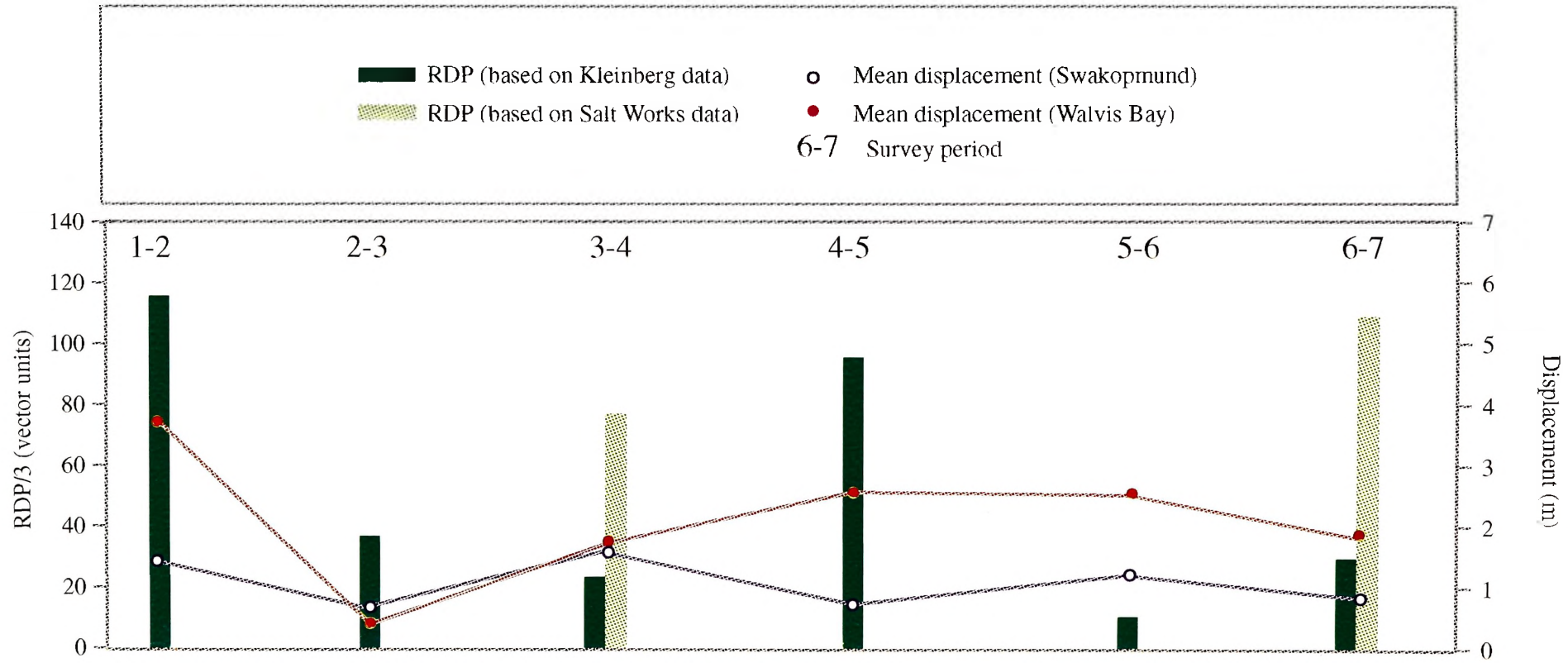
The interaction between wind direction (RDD) and velocity, and sediment supply is important in this case. If RDP is high, then sediment transport is likely to increase accordingly, and may result in an increase in downwind dune volume for those dunes exposed to winds from this resultant drift direction (RDD), given a sufficient upwind sediment source. If the wind direction is such that dunes are not exposed to an upwind sediment supply, then dune volume may possibly decrease with this high RDP. This interaction, in part, may explain why dune volume and RDP do not appear to follow coincident trends in either study area.

The survey periods 3-4, 5-6, and 6-7 have a low RDP/DP ratio when Kleinberg data is used in the calculation, a result which indicates high directional variability. This variability may in part account for the discrepancies in the relationship between displacement and RDP, particularly since the strongest divergence between displacement and RDP coincides with the periods of low RDP values. If winds are highly variable and of a relatively low velocity, then dune movement would be expected to be low. This occurs during the survey periods under discussion; according to the RDP (the measure of the magnitude of the resultant drift direction, RDD), potential sand transport was low during these survey periods, based on Kleinberg data. However, corresponding dune displacement did not decrease.



**Figure 6.5 RDP and dune displacement for the Walvis Bay and Swakopmund dunes**

Figure 6.6 RDP and mean dune displacement for the Walvis Bay and Swakopmund dunes



These discrepancies in displacement, volume, and RDP may be a reflection of the localized variations in the wind regime. The Kleinberg weather station is located in a 'transitional' area, where strong coastal and inland winds converge, resulting in a high degree of variability in both wind direction and velocity. The Walvis Bay study area may also be situated within this transitional zone; consequently, the relationship between dune displacement direction and magnitude, and wind characteristics is not particularly strong (see Figure 4.4, Chapter Four).

By comparison, the Swakopmund dunefield is located much closer to the coast, where strong coastal winds influence the direction and magnitude of dune displacement. Displacement is comparatively low for the Swakopmund dunes, indicating that local 'sheltering' effects from adjacent dunes may be reducing the effectiveness of these winds. The RDP/DP ratio provides an indication of regional wind variability but does not allow for localized variations in the dunefields, such as exposure of dunes to these winds. In addition, the topographic 'steering' effect on wind velocity and direction resulting from the adjacent transverse dunes within the Swakopmund dunefield may also account for discrepancies between the calculated RDP and dune displacement.

Error in wind resultant calculation provides another possible explanation. This error may be from the Kleinberg and/or Salt Works wind data used in the calculations, or there may be error in the actual calculations, although the results were thoroughly checked for errors. For the purposes of comparison with dune displacement, morphologic change and volume, it must be assumed that the calculations are accurate, although there may be systematic errors in the raw data collection.

## 6.4 WIND RESULTANTS AND DUNE MORPHOLOGY

This section summarizes the relationship between changes in dune morphology and resultant drift potential for both the Walvis Bay and Swakopmund dunes. The Fryberger/Dean resultants are used for the comparison. The source of the wind data (Salt Works or Kleinberg) is also noted and the tabulated results are included in Tables 6.2a and 6.2b.

### 6.4.1 Dune Morphology and Wind Resultants: Walvis Bay

The relationship between dune displacement and RDD was examined in section 6.3.2, indicating that no (statistical) correlation existed between displacement and RDD, when displacement was based on the calculated dune centre-point as the basis of measurement. When dune shape is used as the basis of comparison, as in the following section, the relationship with the RDD appears more tenable. In this section, the dune morphologic change and the corresponding wind resultants are presented.

The most significant event over the 5-month study period is the easterly storm of 21 July. All Walvis Bay dunes were of an irregular morphology (Fig. 6.7, 6.8) prior to this event, i.e. they were not domes or barchans, as defined by the accepted criteria presented in Chapter Two. WB1 and WB2 were aligned towards the northeast, while WB3 did not appear to be aligned in any particular direction.

Subsequent to the easterly storm, WB1 maintained a northeasterly slipface, while developing incipient horns facing towards the west. Although the slipface faced the northeast, the bulk of the dune mass shifted in a westerly direction. A similar re-distribution of dune mass also occurred for WB2 and WB3, while overall morphology remained indistinct.

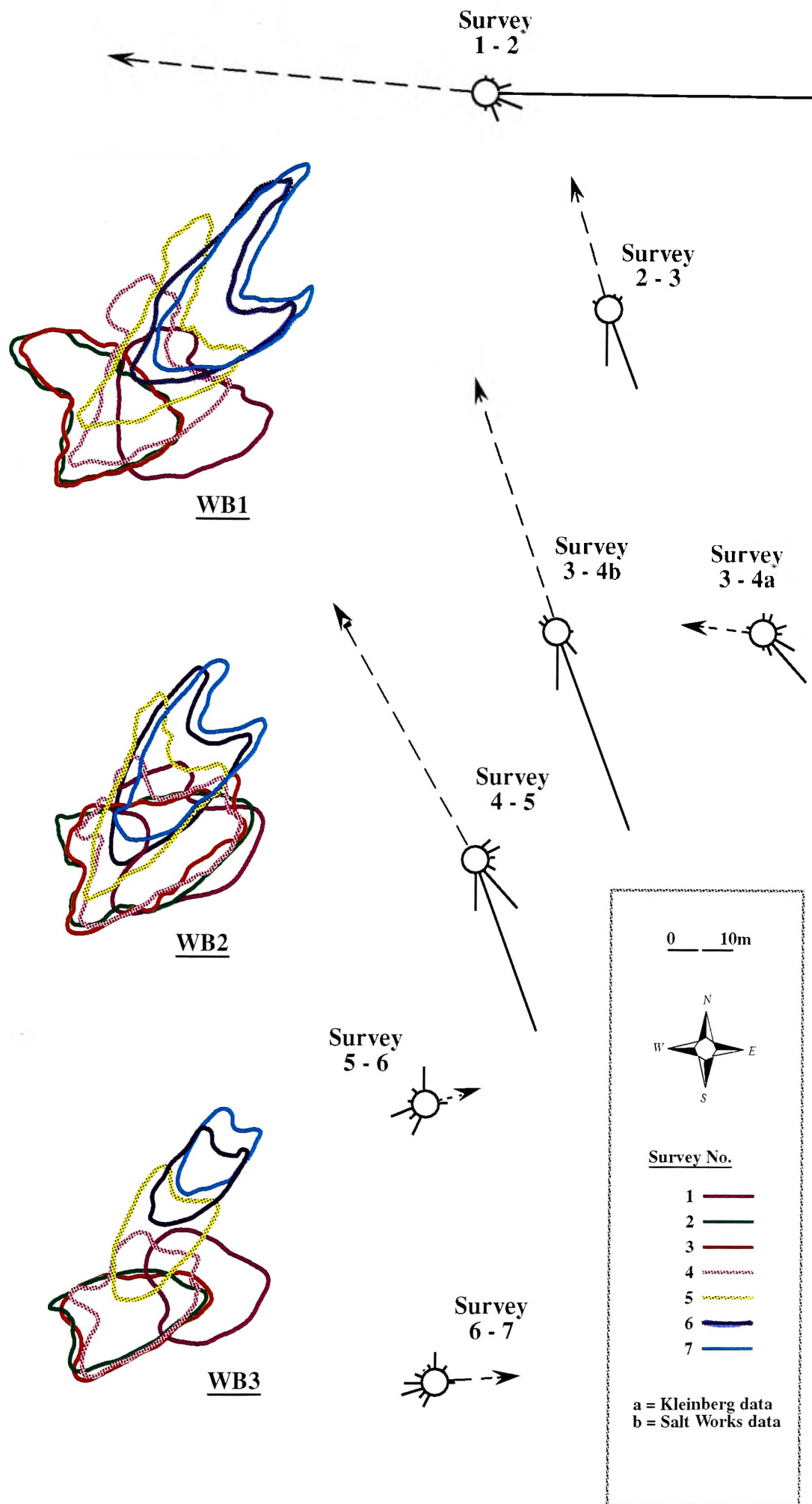
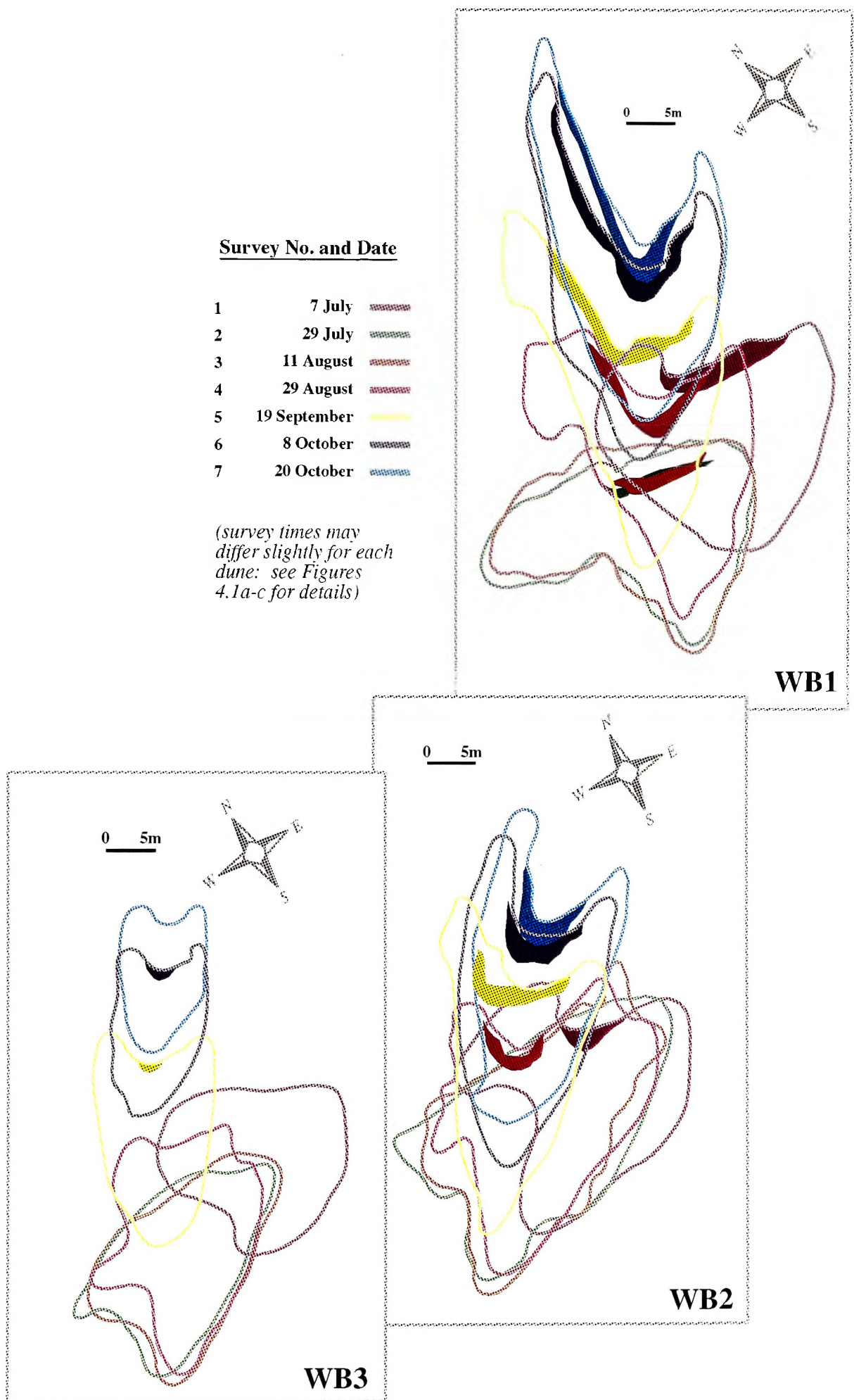


Figure 6.7 Sand roses and dune displacement (Walvis Bay)





**Figure 6.8 Outline of dune shape showing slipface development (Walvis Bay)**

From the end of July until mid-September, the sand roses indicate an RDD (resultant drift direction) towards the northwest, based on Salt Works data. The dunes exhibit a fairly consistent response to this shift, although morphology is once again irregular. From mid-September until the end of the study period (end October) RDD is towards the ENE. The dunes, which all contain a slipface, are aligned in this direction and are beginning to exhibit distinct barchanoid morphology, particularly WB1.

WB3 developed a slipface at the end of the survey period, despite a significant decrease in volume and highly variable winds. WB2 developed a northeasterly-aligned slipface in late August. When the winds shifted towards the east in September-October, the slipface was retained, but the dune appeared to 'bend' more towards the east. As mentioned previously, WB1 had retained a northeasterly aligned slipface despite the strong easterlies in July. This slipface continued to develop both on the leeward side of the dune and along the elongated horn, once the winds shifted towards the northwest and then the east.

It is difficult to distinguish an obvious correlation between dune morphology and the wind resultants, due primarily to the irregular shape of the Walvis Bay dunes over most of the study period. WB1 maintained a northeasterly slipface throughout the entire period, but could only be called a barchan for the last two survey periods. Slipface development and morphologic change followed fairly well the wind resultants derived from Kleinberg data. However, the resultant drift potential, as denoted by the length of the RDD arrow, appeared irrelevant in most cases, with the exception of the wind resultant calculated for the easterly storm period.

WB1 and WB2 each developed and maintained a northeasterly slipface for most of the study period. WB3 developed a northeasterly slipface towards the end of the period. Although all dunes exhibited similar slipface development, some morphological differences are apparent.

These differences may be due to variations in exposure to the varying wind directions, a possibility discussed in previous sections.

#### 6.4.2 Dune Morphology and Wind Resultants: Swakopmund

During most of the study period, the Swakopmund dunes do not develop into either domes or barchans. They remain morphologically indistinct, even when compared to the Walvis Bay dunes, which were not conclusively defineable as domes or barchans in many instances.

The easterly storm in July is reflected in both the displacement direction and morphology of SW1 and SW2 (Table 6.2b and Fig. 6.9). No survey was made for SW3 over this period (9 July-30 July). Similar to the Walvis Bay dunes, pre-storm morphology is indistinct for both SW1 and SW2, and neither dune contained a slipface (Fig. 6.10). After the easterly storm, SW2 did not contain a slipface, and SW3 had developed a slipface aligned in a northeasterly direction, consistent with the wind resultant calculated for the same period. Morphology remained indistinct, although SW2 appeared to be developing incipient horns, similar to WB1.

By the end of August, SW2 and SW3 each had developed a slipface aligned towards the southwest, consistent with the westerly RDD (Kleinberg). For the remainder of the study period, all dunes developed slipfaces aligned towards the northeast, consistent with the RDD, although dune morphology remained indistinct. During early October, SW2 and SW3 exhibited both a well-defined slipface and also areas further along the lee face of the dune where ripples end and minor deposition becomes noticeable. For the purposes of this thesis, these areas are termed 'grainfall zones', since grainfall over the lee slope was observed at the time of the survey (Photograph 6.1). Grainfall zones are smooth, relatively low-angle slopes which do not contain ripples. They are quite distinct from slipfaces. Because these zones are generally at the

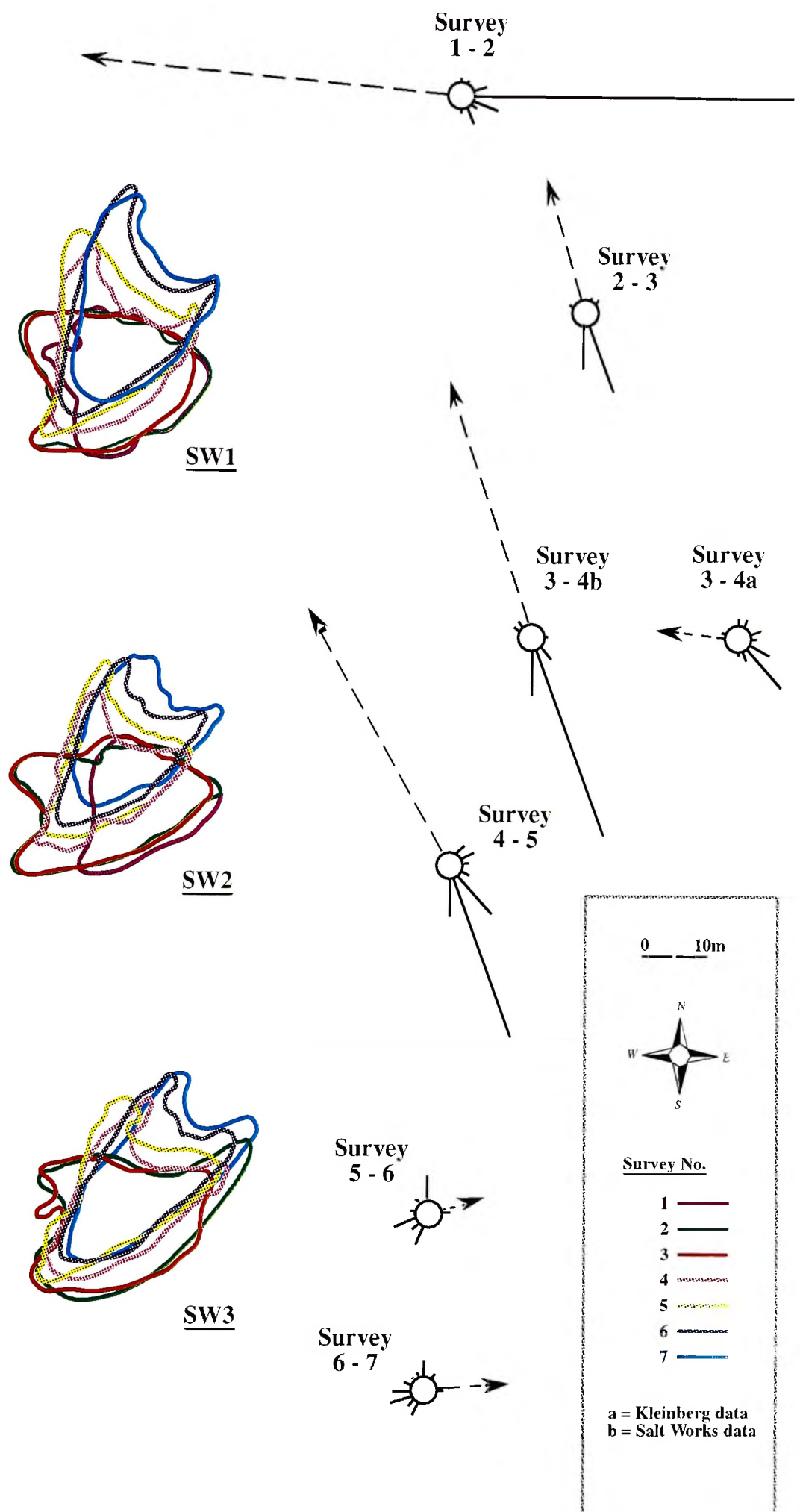
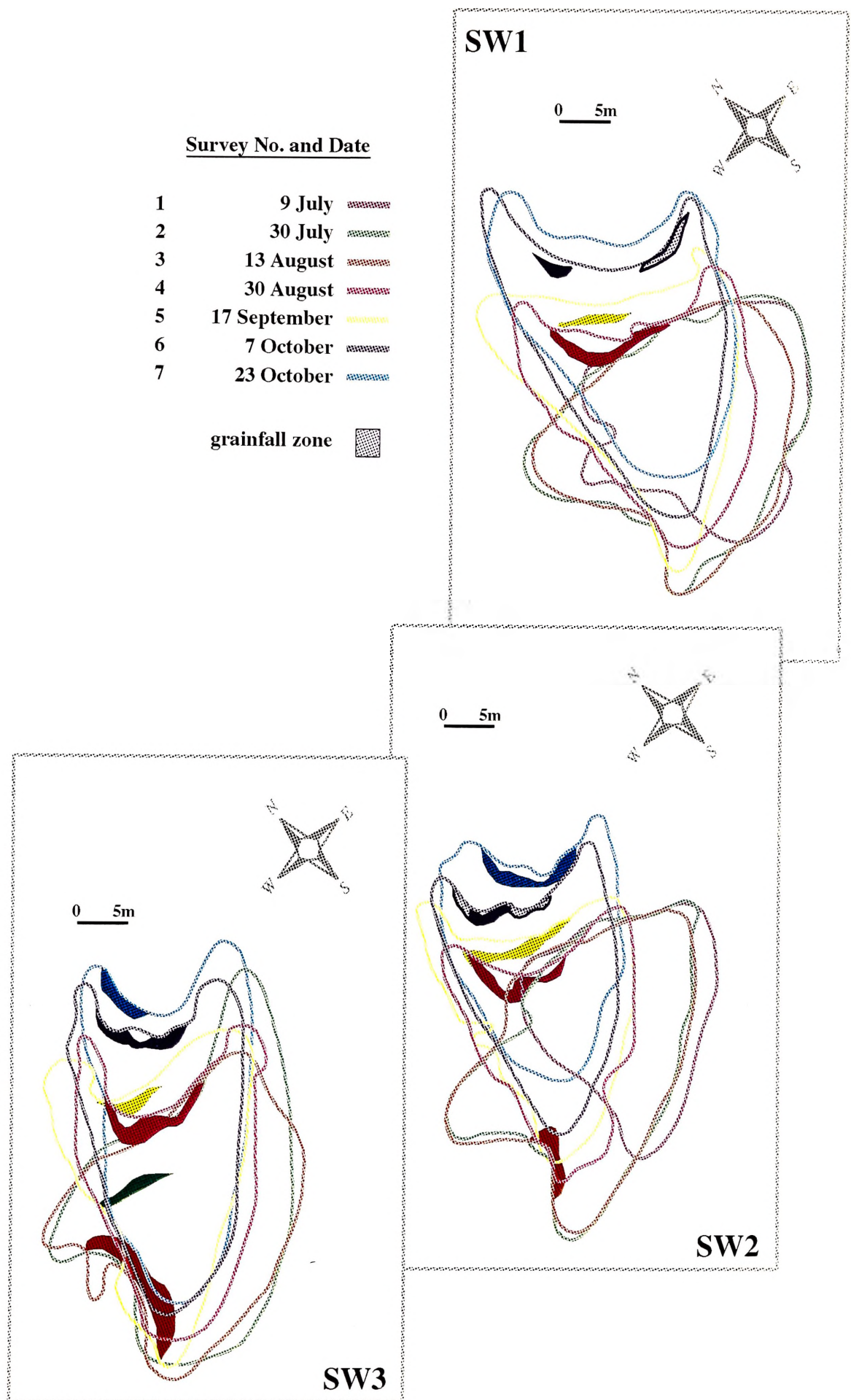


Figure 6.9 Sand roses and dune displacement (Swakopmund)



**Figure 6.10 Outline of dune shape showing slipface development (Swakopmund)**





**Photograph 6.1 Example of grainfall zone**

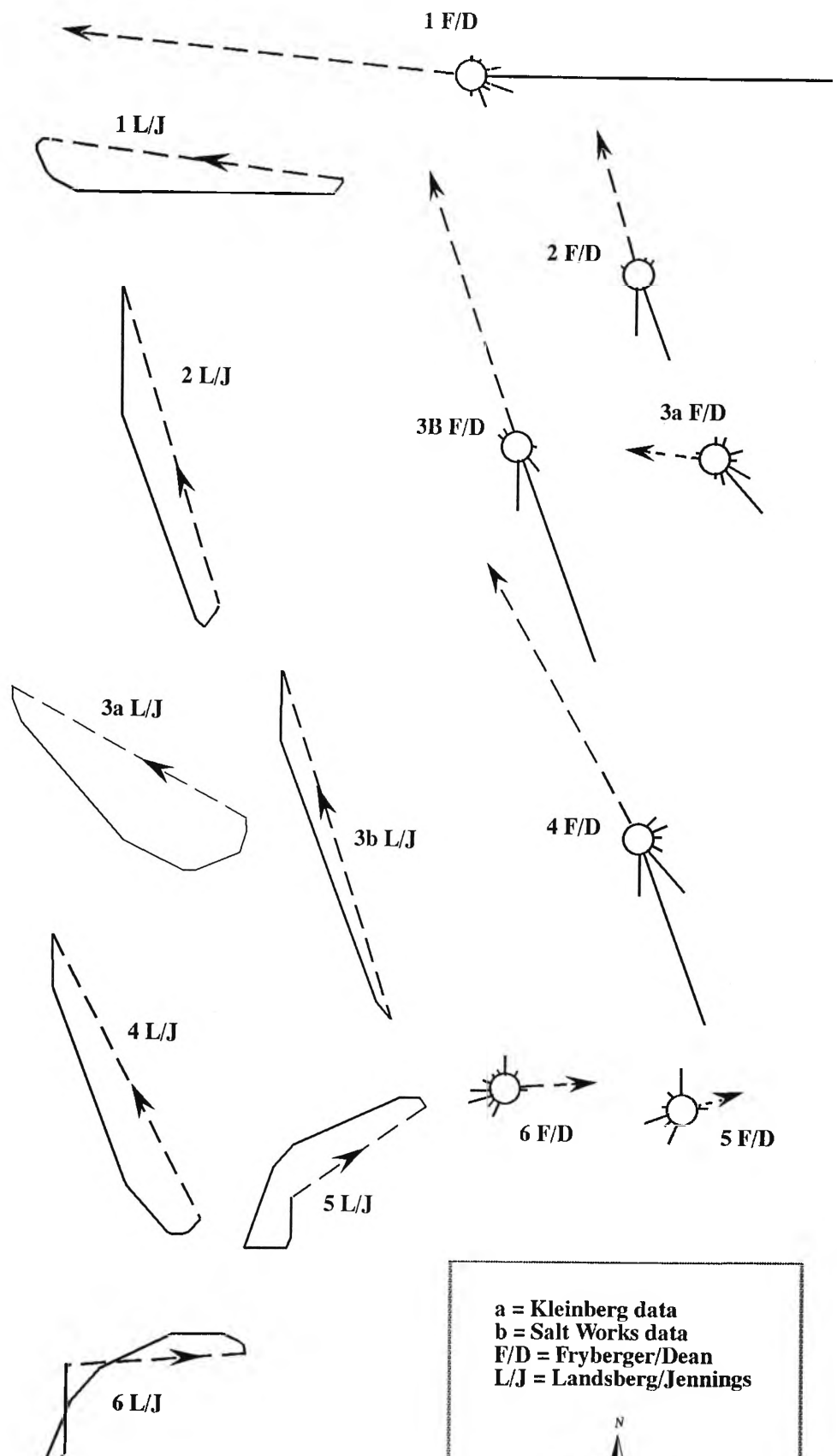
downwind end of rippled lee faces, the existence of these zones may imply a change in wind velocity, flow structure (incipient flow reversal?) and/or sediment transport mechanism.

#### 6.4.3 Dune Morphology and Wind Resultants: Swakopmund and Walvis Bay Compared

Both Walvis Bay and Swakopmund exhibit morphologic changes in response to the resultant drift potential. This is true when either Salt Works or Kleinberg data are used, except during late October (survey period 6-7). At this time, the resultant wind direction of Kleinberg is over 90° different from that of Salt Works (Fig. 6.11). In comparing dune displacement and morphologic change, Kleinberg data were used in preference to that of Salt Works, as the sand rose based on this data exhibited a better correlation with displacement and morphologic development.

The Swakopmund dunes differ from the Walvis Bay dunes in their morphologic response to the changes in wind direction. Development coincides fairly well with the Kleinberg wind resultants, similar to the Walvis Bay dunes. Also like the Walvis Bay dunes, the Swakopmund dunes maintain a northeasterly aligned slipface throughout most of the study period, despite the variations in calculated wind resultants. SW2 and SW3 both developed and maintained this slipface over a longer period compared to SW1, although dune morphology for all dunes was indistinct over almost the entire survey period.

SW1 and SW2 also contained 'grainfall zones'. The presence of this grainfall (non-rippled zone) may indicate that the dune, under a wind of consistent direction, may possibly evolve into a full slipface over time. However, the directional variability of the wind exhibited during the short inter-survey periods possibly prevented the development of this grainfall zone into a slipface. During October, RDD varied considerably for Salt Works (southeasterly) and Kleinberg (westerly) weather stations. The grainfall zone along the eastern edge of SW1 indicates the possible influence of southeasterly winds. Over the same period, a full slipface had developed



**Figure 6.11 Comparison of Fryberger/Dean (F/D) and Landsberg/Jennings (L/J) sand roses and wind resultants**

*Note: see Figure 5.3 or 5.4 for measurement dates.*



along the western edge and slight elongation of the edge was noticeable, indicating that west/southwesterly winds also exerted influence on dune development. SW2 and SW3 during this time exhibited fairly consistent slipface development along the western edge. These differences in dune morphologic development may reflect the relatively high degree of variability of winds in this area, or may indicate the influence of localized controls, particularly exposure of individual dunes to the prevailing winds.

Slipface development at Walvis Bay appeared to develop in response to south/southwesterly wind directions. This is particularly true for WB1. DP and slipface development did not follow any pattern. This high DP (400) following the July storm did not cause a westerly-aligned slipface to develop. In fact, WB1 maintained its northeasterly-aligned slipface, which continued to develop, irregardless of variations in DP and RDD.

#### 6.4.4 Dune Classification: Walvis Bay and Swakopmund Dunes

The discrepancies in results obtained from both the Kleinberg and Salt Works stations indicate the level of variability in wind patterns in the area, and also imply local exposure to winds is a strong influence on dune development and displacement. The low RDP/DP ratio (Table 6.1) based on Kleinberg data, reflects the variable nature of the winds in the 'transitional' Walvis Bay area, as observed by Lancaster (1985).

Dune morphology for all dunes over the majority of the study period was not distinctively barchan or dome. This is in response to the inherently variable regional winds and localized controls already discussed. During the study period, which constitutes five months of the year, the winds were mainly from the southeasterly sector. However, the winter easterly storm winds, although short in duration, during the study period exhibited velocities of up to 65km/hour (Namib Times, 21 July, 1989; Fig. 6.11, No. 1). These winds were sufficient

enough in intensity to cause dune re-alignment and displacement over a very short period of time. Dune morphology was also altered in response to these winds. Once the southeasterly/southwesterly winds again predominated, the dunes responded by again re-aligning in the resultant wind direction.

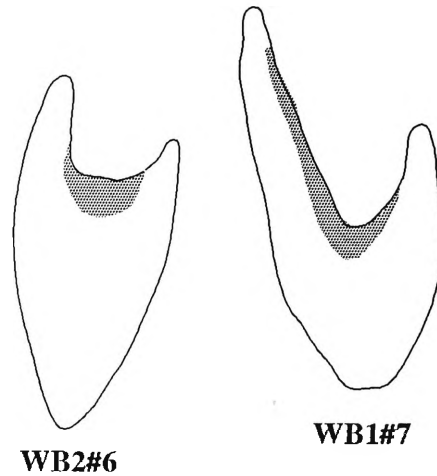
The dune forms resulting from this wind regime maintained their indistinct morphology for most of the study period. Although the Swakopmund dunes were classified as domes (Ward, pers. comm., 1989), for most of the study period they exhibited various phases of slipface development. The presence of a slipface does not allow a dune to be classified as a dome, since a dome, by definition, does not contain a slipface. The Walvis Bay 'barchans' also do not exhibit a morphology consistent with the definition of a barchan (see Figure 2.1, Chapter 2), until October. Because of the length of duration of these indistinct forms and the inherent variability of the wind regime, it is possible to re-classify these forms as 'transitional' domes and barchans (Fig. 6.12 and Tables 6.2a and 6.2b).

The criteria for this classification are listed on Figure 6.12. The accepted criteria for both domes and barchans are also included. The two additional classifications, transitional domes and transitional barchans, are based on the observed morphology of the Namib dunes, which occur in response to the local wind regime. A dune may be classified as a transitional dome if the shape is irregular and a slipface is not present. A transitional barchan is also of an irregular shape, but contains a slipface. The examples in Figure 6.12 are taken from actual Namib dune morphologies exhibited during the study period.

These classifications are 'transitional' because of the evolutionary nature of the dome-barchan relationship. Transitional assumes that over time, a transitional dome or barchan will evolve into either a dome or a barchan. The controlling factors in this evolutionary process are wind direction and sediment supply. Given a constant wind direction and sediment supply, a dome

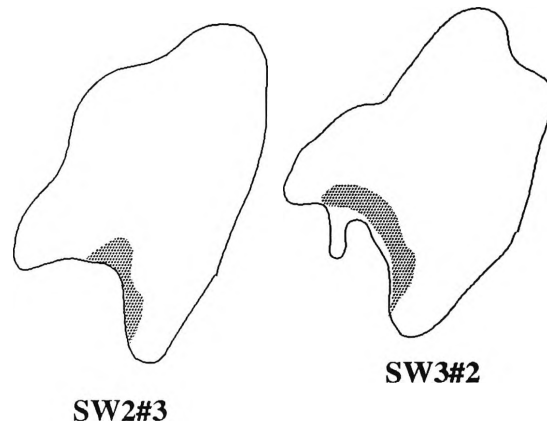
### **Barchan**

crescentic shape with a slipface, can be asymmetrical, i.e. exhibits horn elongation due to oblique winds. Usually occurs under uni-directional wind regimes in areas of limited sand supply



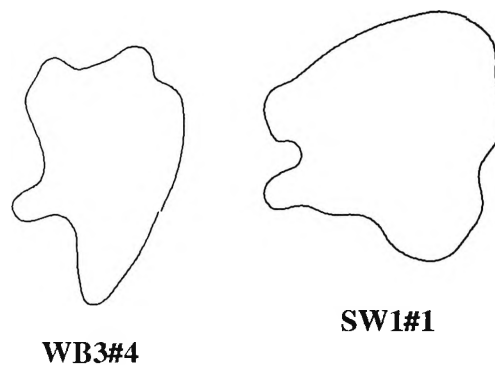
### **Transitional Barchan (TB)**

irregular or slightly barchanoidal in shape, one or more slipfaces. Occurs in areas where windflow is predominantly uni-directional, but where seasonal and daily variability may be significant



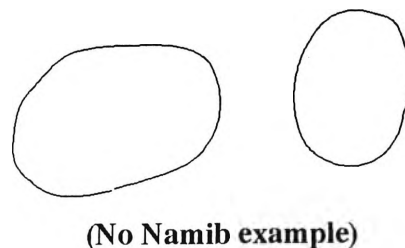
### **Transitional Dome (TD)**

irregular shape, no slipface. Occurs in areas with predominantly uni-directional wind flow, but where direction may fluctuate significantly on both a daily and seasonal basis



### **Dome**

low circular or elliptical mound with no slipface. Usually associated with uni-directional wind regimes



**Figure 6.12 Dune classification scheme**

will evolve into a barchan (McKee, 1979; King, 1918). The variable wind regime observed during the study period resulted in dune forms which did not exhibit true dome or barchan morphology, although as wind direction maintained a constant direction towards the end of the study period, the Walvis Bay dunes became true barchans, emphasizing the importance of a constant wind direction in the development and maintenance of a barchan.

## 6.5 CONCLUSIONS

This section summarizes the major findings presented in this chapter.

1) Both the Landsberg-Jennings (LJ) and Fryberger-Dean (FD) methods of sand transport measurement may be limited in their applicability. In this thesis, the resultants were calculated for the time between each survey period, for a total of six resultants which represented five survey months. The FD method is useful for determining regional wind characteristics, and associating these characteristics with specific dune forms. However, in the case of the Namib dunes, the dune forms vary between survey periods, as do the associated wind regime classifications (Table 6.1). Figure 6.3 shows Fryberger's (1979) classification of the Walvis Bay wind regime as narrow unimodal, consistent with the dune types in the area, but not with the findings presented in Table 6.1. It may be concluded from this discrepancy that the validity of the method utilized in the calculation of the resultants may be limited to longer time periods, and only be accurately applied at a regional scale.

2) Both the LJ and the FD methods may be used in the calculation of resultant sand transport, and should show minimal variation in their results. This is certainly the case for the resultants calculated for the Namib wind data. Both methods indicate almost identical resultant directions. However, the FD method, unlike the LJ method, allowed the determination of a quantified resultant drift direction (RDD), expressed as resultant drift potential (RDP), the magnitude of

which was indicated by the length of the RDD vector. These quantified resultants represent the amount of sand that potentially may be transported under the given winds. Obviously, if the vector is comparatively long, then sand transport potential should be comparatively high, a situation expected to result in greater dune displacement. However, as the results in Tables 6.1a and 6.1b indicate, the potential sand transport and actual dune movement are not consistent in most instances, with the resultant for survey period 1-2 providing the only reasonable correlation with actual wind velocity and corresponding dune displacement.

These inconsistencies may be explained by localized variation in wind velocities and exposure to these winds. Although the potential sand transport is quantifiable, it does not necessarily mean that all dune movement can be explained by this calculated figure. Too many local controls exist that will affect dune movement, such as sediment supply, grain size and density, limited exposure to high velocity winds, and 'steering' effects of adjacent dunes. Certainly in the case of the Namib dunes, local differences between the study areas are apparent, particularly with regards to dune exposure to sand transporting winds. The Swakopmund dunes were far less exposed to strong winds than the Walvis Bay dunes, due to the adjacent transverse dunes. In addition, the bulk specific gravity of the Swakopmund dunes ( $3.88 \text{ g/cm}^3$ ) is significantly greater than that of the Walvis Bay dunes ( $2.76 \text{ g/cm}^3$ ). This higher density and grain size (0.21mm, compared to 0.18mm for Walvis Bay) may mean that sediment transport will be relatively limited compared to Walvis Bay, particularly when exposure to sand-transporting winds is reduced. A number, such as the resultant drift potential (RDP) of Fryberger-Dean (FD), may not be sufficient to explain dune displacement, both potential or actual, in this instance.

(3) DP, RDP and dune volume do not exhibit any consistent relationship, the one exception being survey period 1-2. Subsequent to the July storm, volume increased for all dunes. Drift potential was also high. This increase in volume may be due to the exposure of sediment lying upwind of the dunes, to these strong, infrequent easterly winds.

Dune displacement does not increase with increasing drift potential or resultant drift potential for either Walvis Bay or Swakopmund dunes. It is intuitively believed that a greater drift potential would lead to an increase in sediment transport and dune displacement. The results in this case do not show this to be true, again illustrating the effects of local influences on wind velocity and direction, and subsequent dune movement.

(4) Slipface development and RDD varied between study areas. SW2 and SW3 had developed slipfaces in response to the easterly winds in August, despite the short duration and low intensity of these winds. Prior to this slipface development, the dunes had re-aligned in a westerly direction in response to the July easterly storm, but had not developed a slipface. Despite the lack of slipface, dune displacement was high and volume increased, implying a re-distribution of total dune mass. These winds were not of sufficient duration to allow the development of a slipface. However, dune alignment was still sufficiently westerly to allow a slipface to develop during the low-intensity easterly winds which occurred in August. Although these winds may not have been strong enough to cause slipface development without prior westerly alignment of dune mass, they were sufficient enough in intensity and duration to facilitate and maintain a slipface in this case.

None of the Walvis Bay dunes developed a slipface during July-August, although WB1 maintained its northeasterly-aligned slipface despite the strong easterly winds. This is in spite of the fact that the Walvis Bay dunefield was more exposed to these winds than Swakopmund.

After a period of short-term changes in wind velocity and direction (end July to mid-September) wind direction (RDD) 'stabilized' and became predominantly westerly. RDP was also low, indicating the low wind velocity during this period. All dunes developed northeasterly slipfaces during this time, with WB1 exhibiting marked horn elongation in response to the low intensity westerly winds. These results imply that a high intensity/low frequency event is as effective in facilitating morphologic change in some cases, as high frequency/low intensity events. That the

dunes did not develop slipfaces during the time of variable winds also implies that in addition to wind velocity, wind direction must be maintained for a minimum length of time to affect a change in dune morphology.

(5) A new dune classification scheme was introduced in this chapter. This scheme includes two new 'transitional' dune types, which were based on observations of dune morphology in both of the Namib study areas. The new dune types reflect forms which cannot be classified by existing criteria. Because these forms are maintained over a reasonable length of time they are considered to be a separate dune type.

The new dune classifications presented in this chapter (Fig. 6.12) are based on the distinctively 'irregular' morphology exhibited by the Namib dunes over a 5-month period. These two new classifications represent two distinct phases in the dome-barchan evolutionary process. These forms are recognizable as distinct under variable or bi-modal wind regimes, such as those which occur in the Namib. Should these dunes maintain their irregular form over time, they may be classified as 'transitional' indefinitely, until changes in wind direction are of sufficient duration to allow the continuation of the dome-barchan-dome evolutionary process.

## **Chapter 7**

### **DYNAMICS OF DOME AND BARCHAN DUNES**

#### **7.1 INTRODUCTION**

Many aspects of barchan and dome dune dynamics and morphology remain largely unknown. One example is the minimum size at which a dome will develop a slipface, and what conditions control the maintenance of this form. In addition to dune size and slipface development, the controls of dune shape on sediment transport and dune displacement also pose a difficult area of study (Cooke et al., 1993). The evolution of domes to barchans in the field has been observed in several areas around the world (Hastenrath, 1967; King, 1918; Mainguet, 1991). Attempts have also been made to model the process (Howard and Walmsley, 1985; Wipperman and Gross, 1986). Although this evolutionary process is acknowledged, the "most serious problem with evolutionary-change models is their aerodynamic explanation" (Cooke et al., 1993, p. 331). The aerodynamic controls of barchans have been observed and modelled to a reasonable degree (see Chapter 2). By contrast, little is known about the aerodynamics and geomorphological dynamics of dunes without a slipface.

The data presented in this chapter attempt to assess some of the many questions regarding the aerodynamics of dome dunes, and to further evaluate the evolutionary relationship between domes and barchans, including the differences in wind flow over each form. To do this, a series of flow experiments were conducted in the Swakopmund study area. In conjunction with the flow experiments, sand transport measurements were also conducted to quantify sand erosion/deposition patterns over dunes, and over lee slopes containing a slipface and over lee slopes without a slipface. The methodology employed in these experiments, and the results, are presented in the following sections.



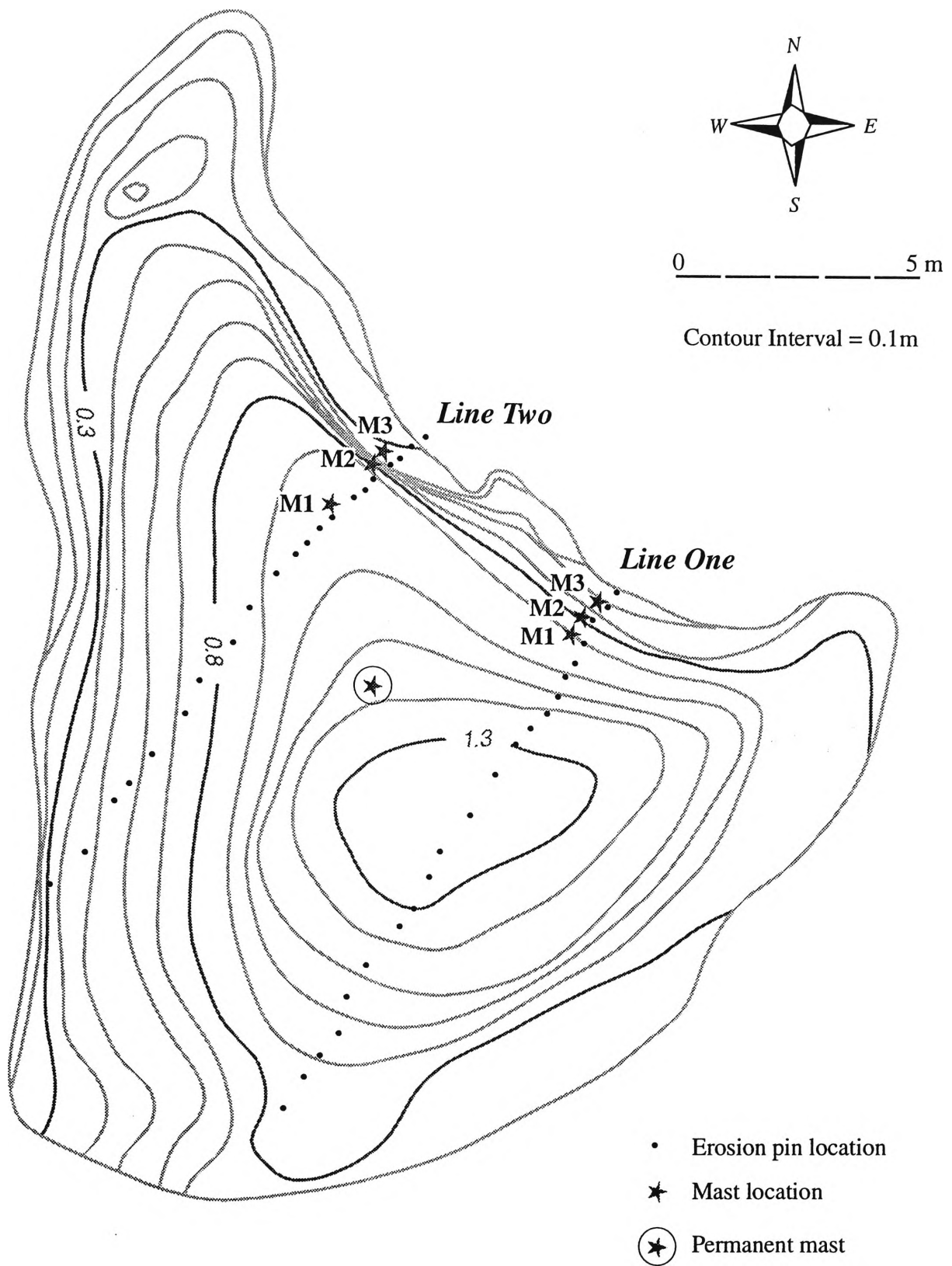
### 7.1.1 Methodology

Three separate wind flow experiments were conducted over dome, barchan, and 'transitional' dunes, during August and October, 1989. Sand transport rates and erosion/deposition patterns were also monitored in conjunction with the flow experiments. Wind flow experiments were conducted in both August and October, 1989, over Swakopmund dunes 1 and 3 (SW1 and SW3). These dunes were selected because each contained both a well-developed slipface and an area where a slipface was not present. This situation was considered ideal for simultaneously comparing flow patterns over both forms.

Wind velocities for all experiments were measured using a maximum of 12 Rimco, low inertia, miniature cup (32mm diameter) anemometers. Anemometer positions varied for each experiment, except for a permanent mast located near the center of the dune. Corresponding erosion and deposition patterns across the dune were measured using lines of 1mm diameter, copper, erosion pins set up at known heights and distances apart, with measurements generally taken at 30 minute intervals.

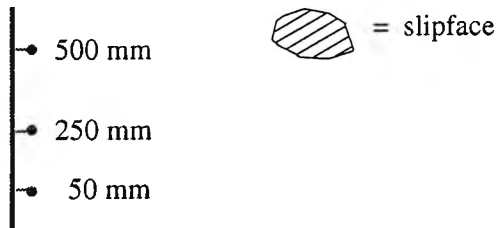
### 7.2 EXPERIMENT 1 (27 August 1989)

Experiment 1 was conducted to examine flow over the crest of two crest-lee slope types (a dome and a barchan), to determine the differences in flow behaviour. Barchans commonly exhibit flow separation over the steep lee slope, which is usually a slipface; by contrast, dome dunes represent a dune type apparently exhibiting little to no flow separation, at least at low slope angles. Since these two dune types exist as part of an evolutionary sequence, it is therefore hypothesized that flow conditions must play an integral part in the development of a barchan from a dome, and vice versa. In addition, dune morphology may influence flow behaviour, which will then lead to a further adjustment of form. In essence, the relationship



**Figure 7.1 Location of erosion pins and Masts - Experiment One**

Masts, with anemometers,  
with heights as shown.  
(Masts numbers are noted  
above each mast).



Note: The positions of the masts are correct; the heights  
of the anemometers are schematic only.

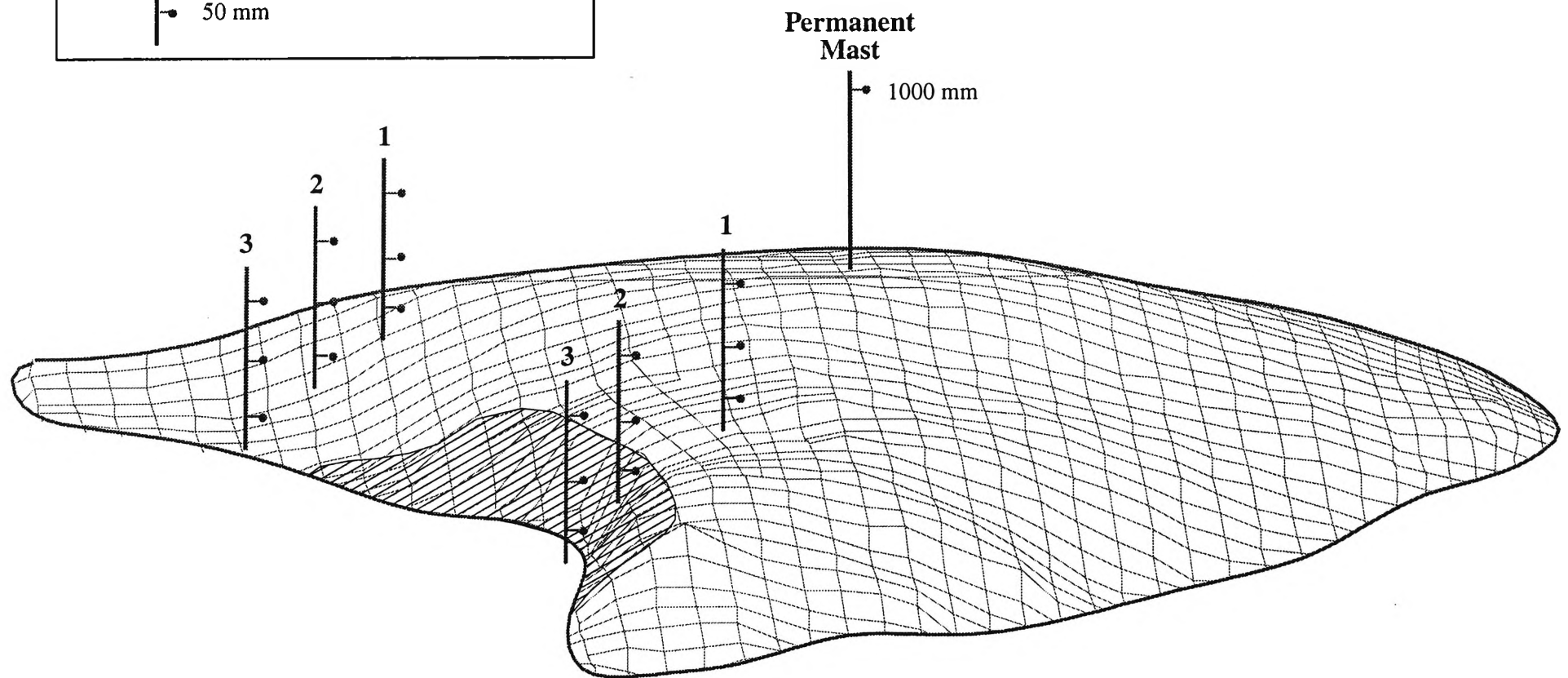


Figure 7.2 Location of masts - Experiment One

between form change and flow behaviour is one of constant change and adjustment. Just how and when a slipface will develop as a result of flow behaviour, and the associated erosion-sedimentation patterns, has not been previously observed in the field. The following experiment attempts to determine what flow conditions are required to induce this change.

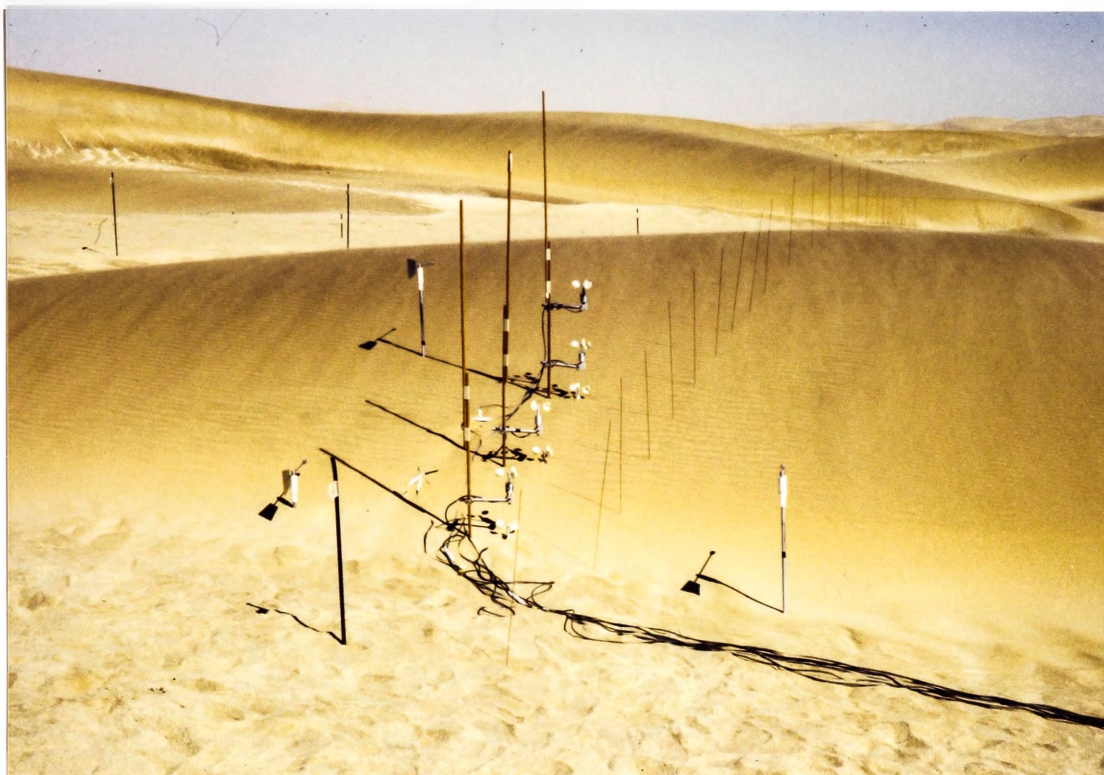
The first experiment was conducted on 27 August 1989 on SW 1 dune (Photograph 7.1 and 7.2). Two lines of erosion pins were placed across the dune along the long axis and parallel to the ambient wind (Fig. 7.1). Line One extended over an area where a slipface was not present. Line Two ran parallel to Line One, at right angles to the slipface and extending to the edge of the windward slope. Three masts were erected on each line, with three anemometers on each mast at heights of 500, 250, and 50 mm respectively (Fig. 7.2). The permanent mast was at a height of 1000 mm. Figure 7.3 illustrates the anemometer array in relation to the actual dune height and slope angles.

Of the 22 five-minute runs, three typical runs were plotted in Figure 7.4. As indicated by other studies (Inman, 1966; Hesp et al., 1989; Allen, 1982; Bagnold, 1941) the highest wind velocities are found at the dune crest and decrease rapidly down the leeward dune face. This behaviour has also been observed under controlled conditions, i.e. in a wind tunnel (Teunissen et al., 1987; Pearse et al., 1980).

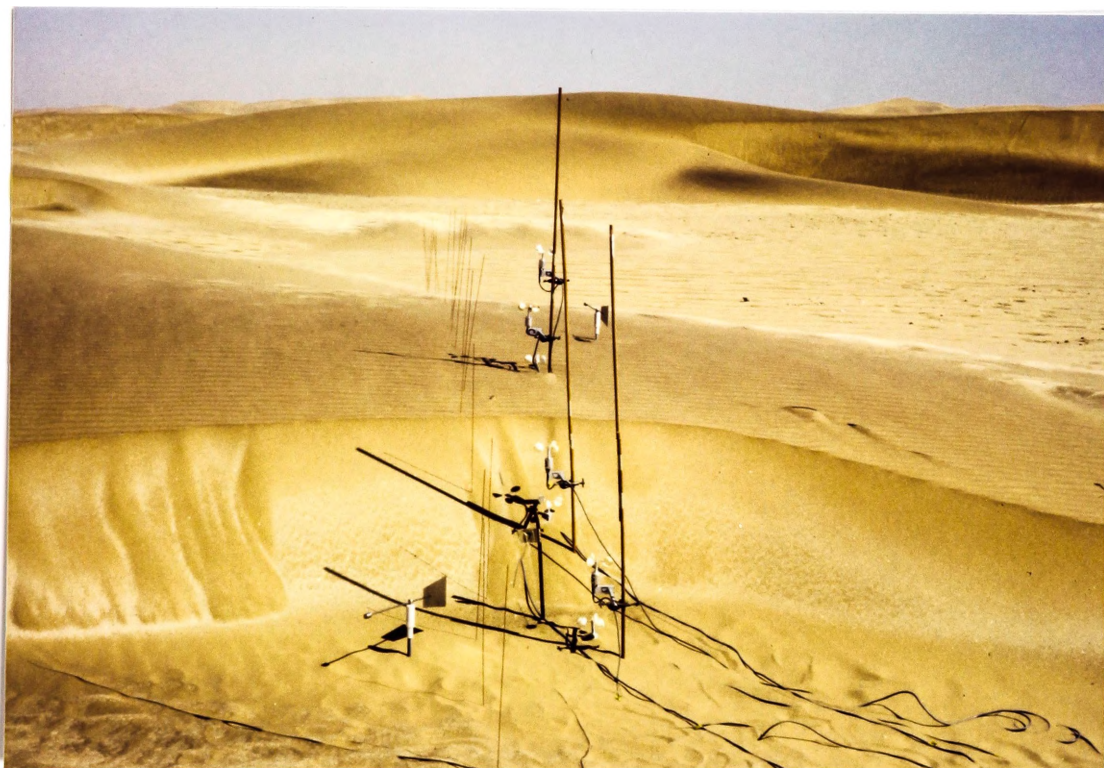
#### 7.2.1 Velocity Profiles (Line One)

The velocities measured along Line One range from less than 2 m/sec (Mast Three) near the base of the slope, to over 8 m/sec (Mast One) near the dune crest, at a height of 250mm. Velocity readings were taken from 12:40 until 18:10. Three of these readings, shown as velocity profiles, are included in Figure 7.4. Over this time period, actual velocities taken





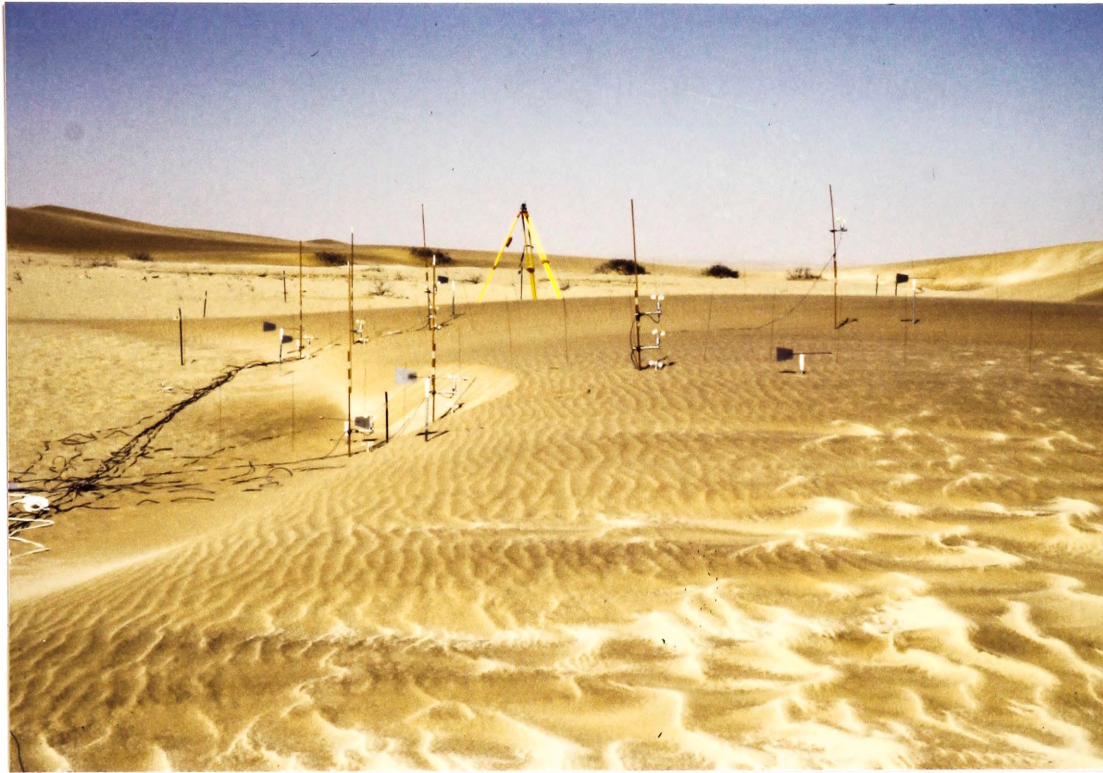
**Line One**



**Line Two**

**Photograph 7.1 Anemometer array, Experiment One (27 August)**



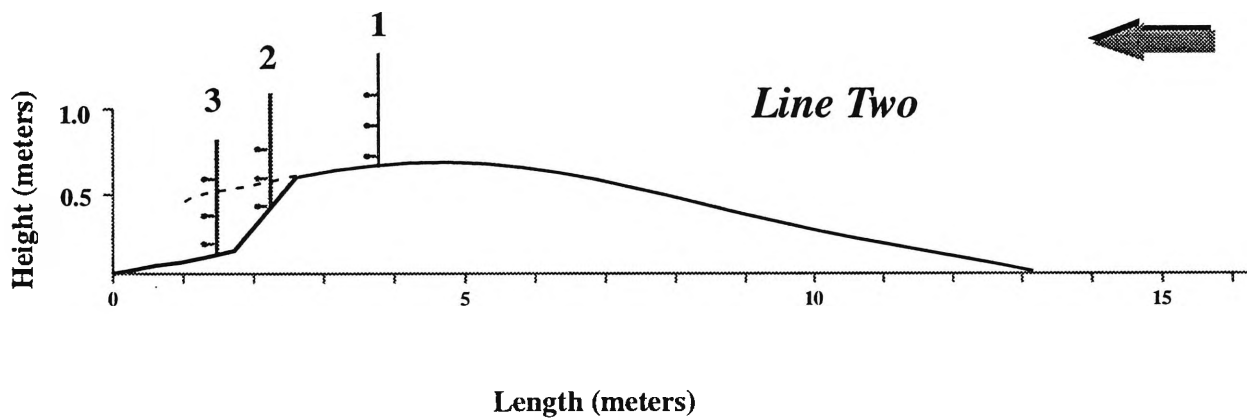
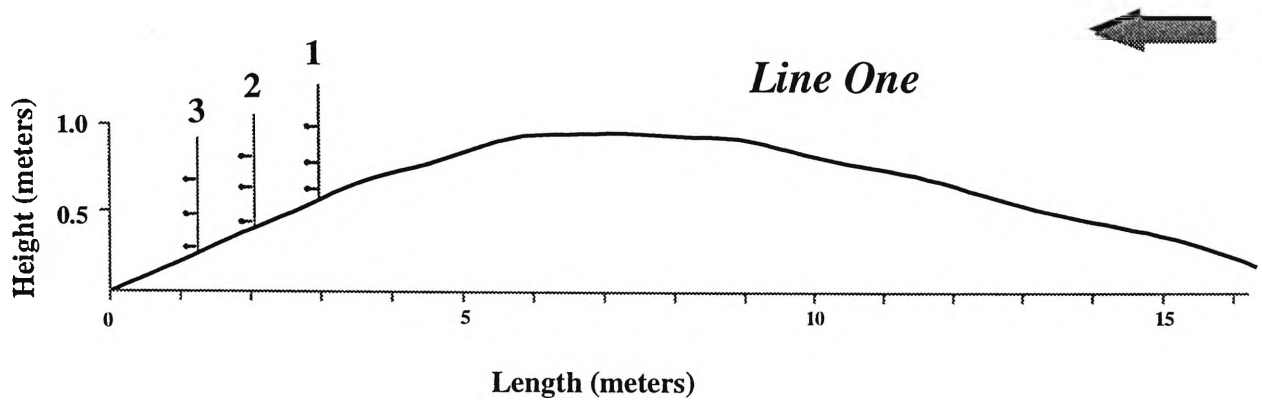


**Looking parallel to the lee slope, Line Two in the foreground**

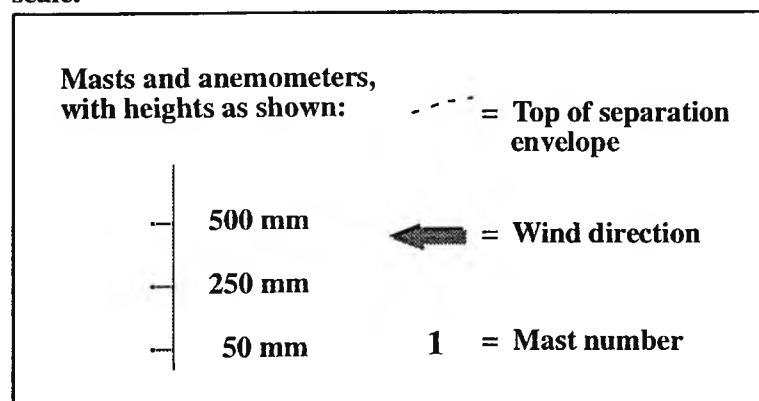


**Looking parallel to the lee slope, Line One in the foreground**

**Photograph 7.2 Anemometer array, Experiment One (27 August)**



Masts, anemometers, and dune measurements are shown to scale.



**Figure 7.3 Location of masts - Experiment One**

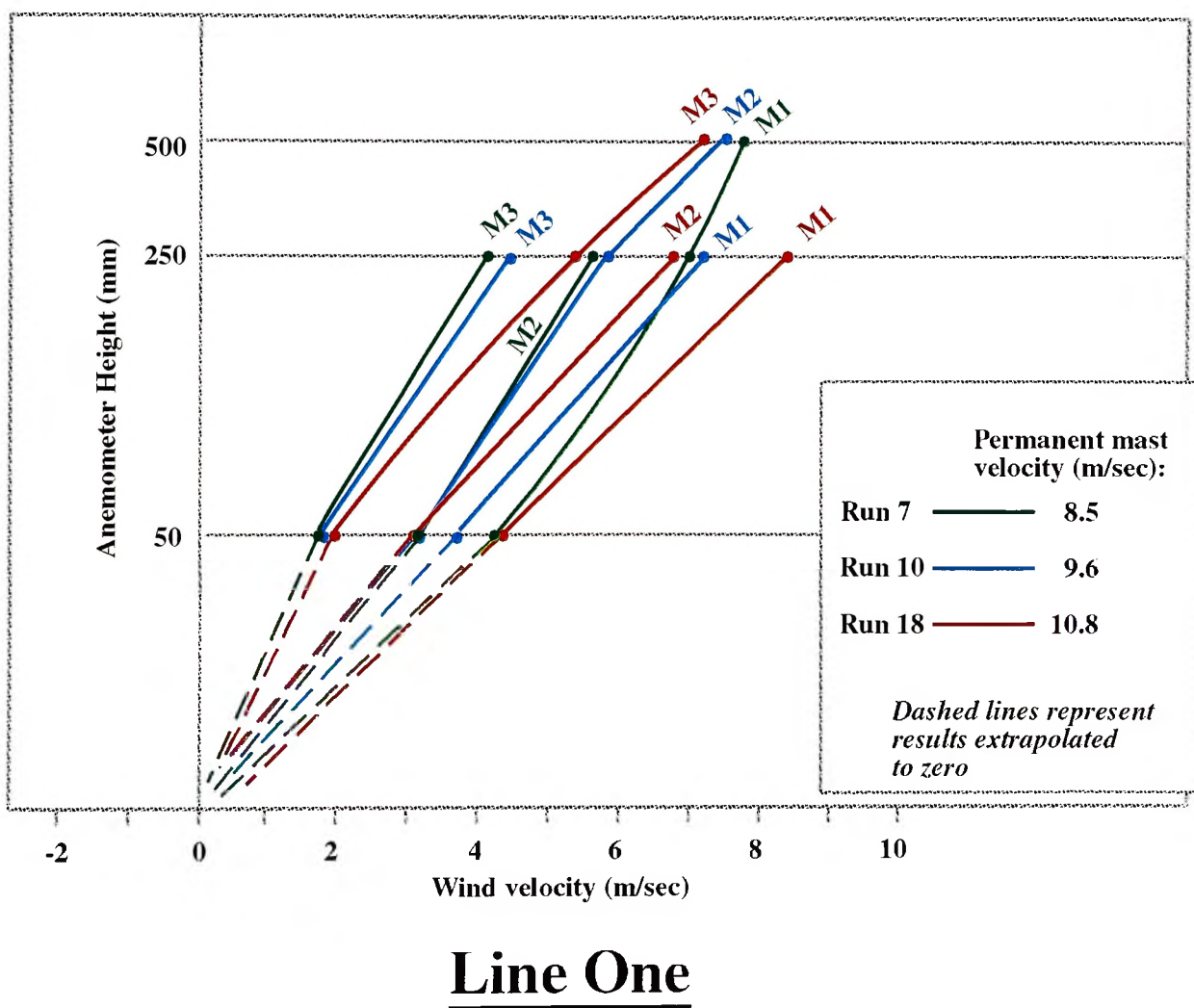
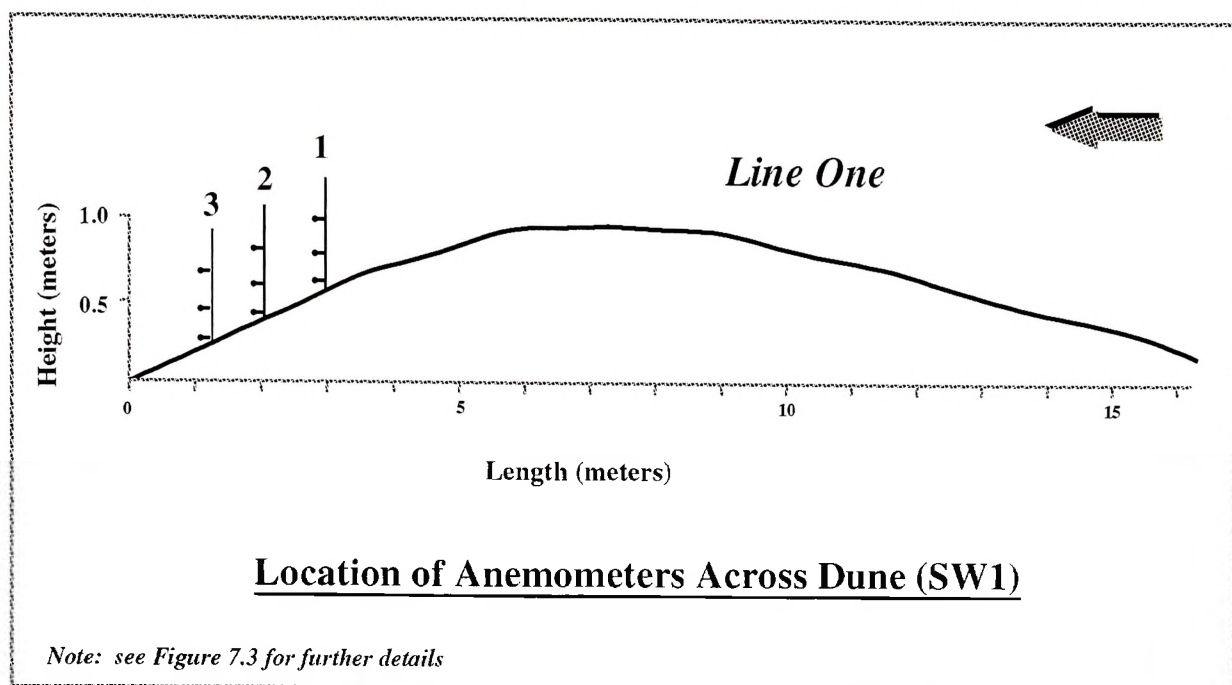


Figure 7.4 Velocity profiles - Experiment One



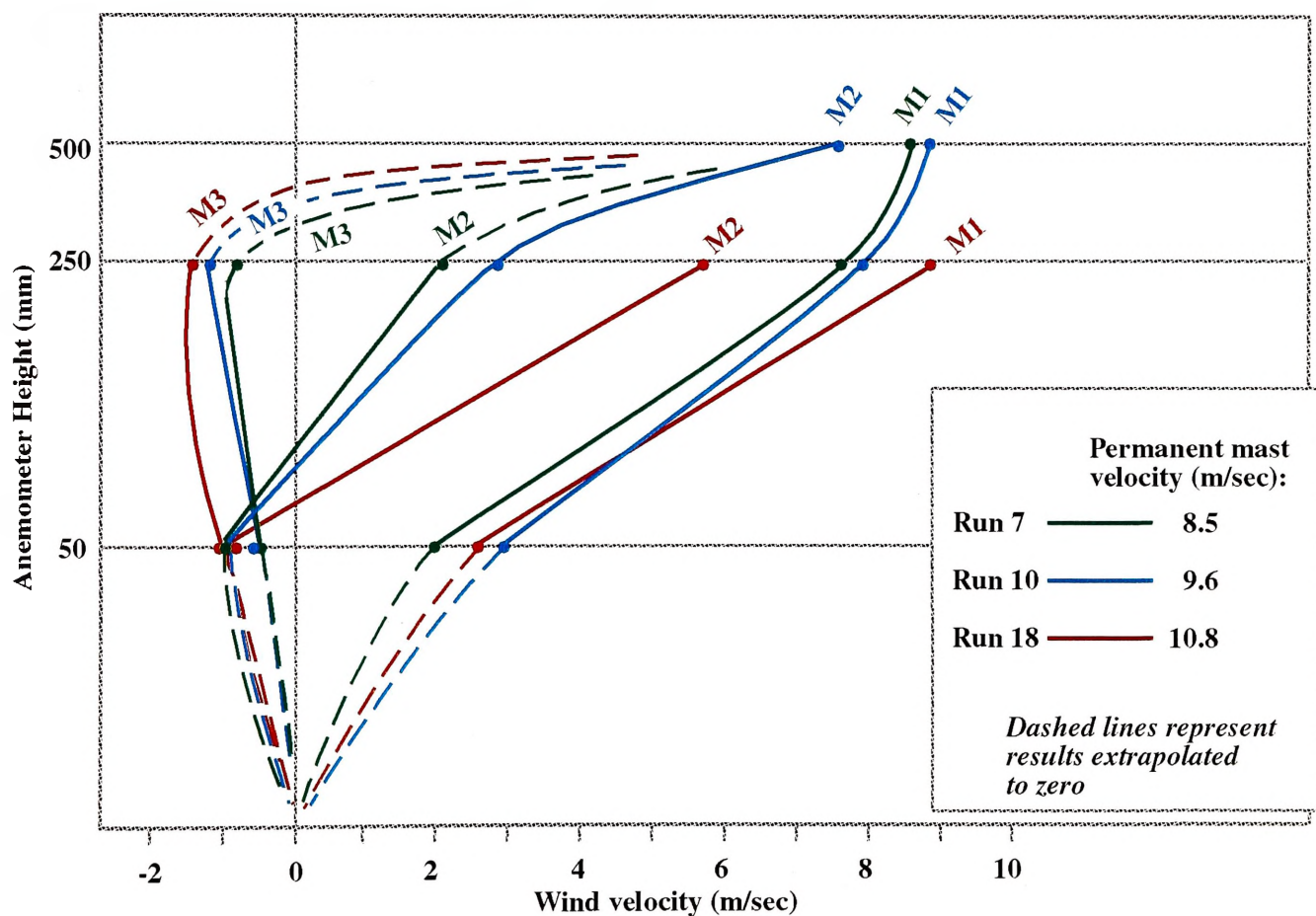
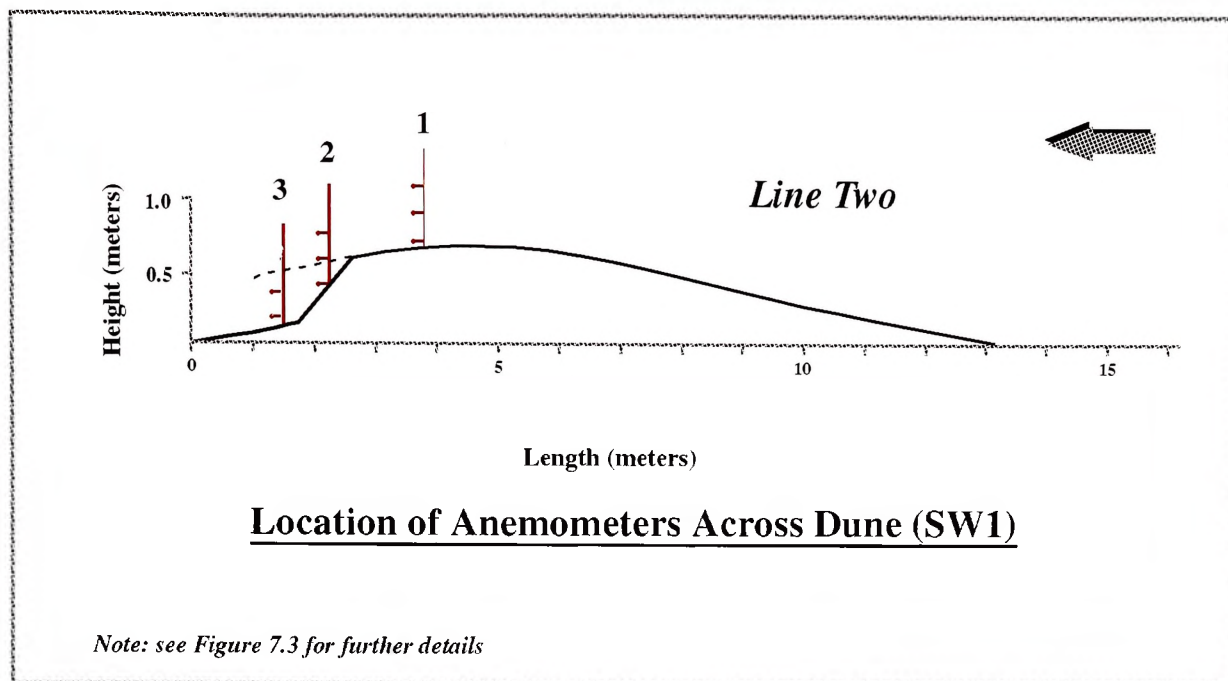
from the permanent mast (at 1.0m height) varied from 4.44 m/sec (13:05) to 10.86 m/sec (16:50) decreasing slightly to 9.55 m/sec (18:10) at the conclusion of the experiment.

The overall structure of wind flow over the dunes does not appear to change markedly as wind velocity increases because the relative difference in the profiles is maintained. However, there is a marked increase in the gradient of the wind profiles at higher ambient wind speeds and this would obviously induce significantly greater shear stress at the bed. Wind speeds are similar for each run at each sampling position near the surface on the lower lee face of this dome-shaped portion of the dune. Observations of the wind vanes at various heights and positions along this portion of the dune indicate that the flow does not appear to be separated on this low ( $16^\circ$ ) slope.

Velocities measured at 250mm on the three masts show a consistent downwind reduction in velocity of 1 to 1.5 m/sec between each mast. This indicates a regular downwind reduction in flow velocity over the lee slope. Velocity increases markedly between 50 and 250mm, particularly for those anemometers located on Mast Two and Mast Three, with velocities at 500mm for Mast One reaching up to 88% of the upwind fixed velocity (permanent mast), compared to 77% for Mast 2 and 68% for Mast Three.

### 7.2.2 Velocity Profiles (Line Two)

Flow behaviour over a transverse dune form is characterized by a drop in velocity at the base of the windward slope. Velocity then increases steadily until it reaches a maximum at the dune crest, followed by a sudden drop in velocity over the lee slope (slipface) and with simultaneous flow separation, characterized by flow reversal. Figure 7.5 illustrates three different velocity profiles over line Two, where some of the latter patterns of flow behaviour are apparent.



## Line Two

Figure 7.5 Velocity profiles - Experiment One

The velocity profiles indicate significant velocity differences exist between those anemometers located at the base of the slipface, mid-slipface, and just upwind of the dune crest (Fig. 7.5). At the lower ambient windspeeds (Runs 7 and 10), the anemometers on Mast Two and Mast Three show little variation in velocity at both the 50mm and 250mm levels. Velocities range from less than -1 m/sec at the base of the slipface (negative flow), to greater than 8 m/sec at the dune crest.

Velocities for the 500mm anemometer on Mast 1 have an average reading of 6.48 m/sec, 97% of the permanent mast velocity (at 1m height). At the same height, Mast 2 has an average velocity of 7.9 m/sec, 80% of the permanent mast velocity taken over the same period. The velocity for Mast 3 is 3.47 m/sec, 35% of the permanent mast velocity. These readings show a significant decrease in wind velocity from the crest of the dune to the leeward slope. Examination of several wind vanes placed in various positions on this line indicate that marked flow separation occurred over the slipface. The higher anemometer (at 250mm) on Mast Two was positioned just above the top of the flow separation envelope, while the lower anemometer (at 50mm) and both anemometers on the Mast Three (located at the base of the slipface) were located within the separation envelope (see Photograph 7.1).

It is apparent that flow separation is more pronounced at higher ambient wind velocities (run 18). In fact, when comparing the difference in velocities of the Mast One and Mast Three anemometers at the 250mm level, the degree of flow separation (or negative flow) between Run 18 and Runs 7 to 10 is similar to the difference in "positive" velocity at the same level on Mast One, perhaps indicating that there may be a relationship between flow separation and wind velocity, i.e. the higher the wind velocity (or positive flow), the greater the degree of flow separation (or negative flow) and the more pronounced the flow separation envelope.

### 7.2.3 Line One and Line Two Compared

Figures 7.4 and 7.5 display typical wind profiles for Lines One and Two. In the experiment, a third anemometer was added to each separate mast at 500mm for two to three runs before being moved to the next mast.

The profiles show that whilst the upwind masts (Mast One) record similar velocities ( $>8$  m/sec) and exhibit a similar structure, the flow over the dune crest is markedly different. In the case of the low slope (dome) portion (Line One), there is a relatively smooth downwind reduction in flow velocity without flow separation. In the case of the slipface (barchan) portion, there is a marked reduction in wind velocity, flow separation and reversal.

Comparisons of runs 7, 10, and 18 on Mast One indicate a significant increase in permanent mast velocity at 1m. However, velocity increases only in small increments at the 250mm level. Velocities at runs 7 and 10 show minimal variation, but when ambient velocity increases over the 9.6 m/sec level, the differences at the 250mm level and above are significant. It is not uncommon to pass a certain ambient windspeed threshold and observe mid-profile and upper velocities increase markedly (Hesp, pers. comm.). With increased mean wind velocity (at the 1m permanent mast), there is a marked increase in flow velocity at all points above 50mm down and quasi-parallel to the dome surface contour. In addition, there is a regular incremental downwind decrease in velocity, irrespective of the ambient windspeed, indicating that flow separation is not occurring over this smooth slope. This is especially so when these profiles are compared to those of Line Two (slipface area), where flow separation and reversal is marked.

The structure, or shape, of Mast Three profiles indicates that flow separation may be imminent, as evidenced by the "concavity" of the profile as it bends towards the left, i.e. towards zero in the 50mm - 0mm extrapolation zone. The extrapolation of the velocity

profile to zero is acceptable, since flow at the surface must fall to zero. That flow separation may be about to occur is a reasonable assumption when these profiles are again compared to those of Line Two. Where marked flow separation occurs, the profiles also bend strongly towards the left and velocity falls to zero at the surface.

In all cases, with increased mean wind speed (runs 7 to 18), the gradient of the profile increases. This would result in increased shear stress over the dune, which would cause a subsequent increase in sand transport. The following sections discuss the results of the erosion and deposition measurements taken over the experimental period.

#### 7.2.4 Sand Transport (Line One)

Erosion and deposition across the domed portion of the dune were measured with a line of erosion pins placed along the long axis of the dune. Measurements were taken in conjunction with the flow experiments. Results indicate that marked erosion occurs across the windward side of the dune, decreasing with distance towards the lee side (Fig. 7.6). At the highest point of the dune, erosion ceases and deposition commences, with maximum sediment accumulation occurring near the base of the lee slope.

Erosion and deposition rates vary both spatially, as discussed above, and temporally, with variations in wind velocity acting as a controlling factor. A strong negative correlation exists between sand deposition and wind velocity; the area of maximum deposition i.e. the near lee slope, is the zone of minimum wind velocity. The dune is approximately 24 metres in length, and the 'transition zone', where the process of deposition of sediment begins to dominate, occurs at 13 metres, just downwind of the dune centreline. Here flow velocity decreases and the slope angle starts to increase. The zone of sand deposition extends across

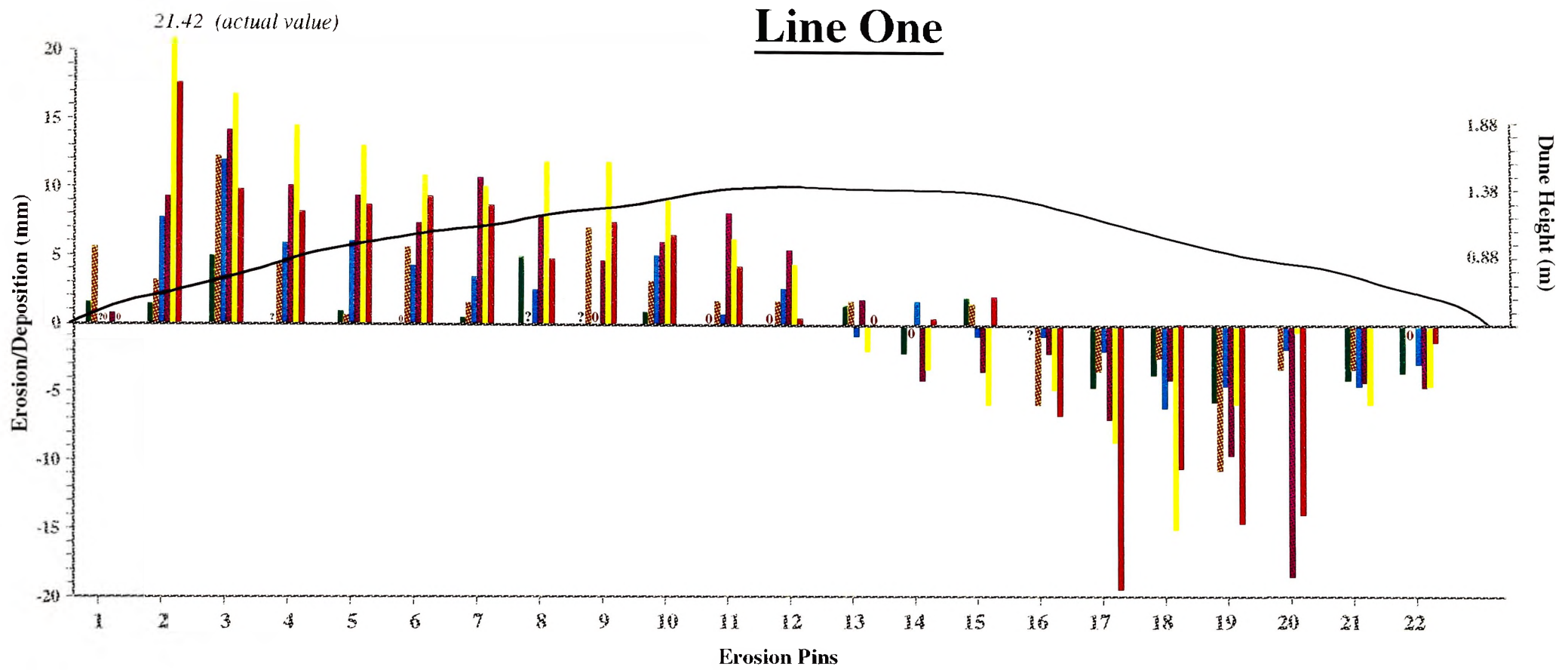


Figure 7.6 Sand transport data - Experiment One

the flow deceleration zone. Therefore, deposition of sediment occurs over approximately 50% of the dune length.

The dune was re-surveyed on 29 August, two days later. The profile change for Line One was minimal. The dune moved forward approximately 0.5m, but without a change in morphology or significant loss of mass, as indicated by the ratio of erosion to deposition (see section 7.2.6 for details). As mentioned above, erosion and deposition are equally distributed across the dune; therefore, not only is the quantity of sediment loss and gain reasonably equal, it is spatially equal as well.

Wind velocities for Runs 1 through 6, measured from the permanent mast anemometer, indicate a steady rise in windspeed until Run 6, when measured velocities decrease. The permanent mast velocities for Runs 1-6 are included in Figure 7.6, as they correspond to the approximate time when erosion pin data was collected. Deposition patterns follow very closely the variations in wind velocities; as velocity increases, there is a corresponding increase in deposition (Fig. 7.6). With the drop in velocity which occurred during Run 6, deposition also decreased. Erosion patterns, however, are not consistent with either velocity variations, as measured from the permanent mast, or with corresponding deposition rates. For example, deposition measurements taken for Run 5 are the highest for the entire measurement period. Erosion rates for the same period are highly variable across the 'eroding' area of the dune. Deposition rates for Run 1 are comparatively low; erosion measurements are reasonably high for the 'eroding' area, and very high just past the base of the windward slope.

### 7.2.5 Sand Transport (Line Two)

Similar to Line One, erosion pins were placed across the length of that portion of the dune with a slipface and measurements taken throughout the flow experiment. Sand transport results for Line Two are markedly different than the results for Line One (Fig. 7.7). Also similar to Line One, the 'transition zone' or area of the dune where erosion ceases and deposition becomes significant, is present near the centre of the dune. However, it is not nearly as defined as in Line One and fluctuates across the relatively flat dune crest. Figure 7.7 indicates that at times erosion occurred up to the 8m position while deposition occurred on one occasion up to the 12m position (excluding the most windward slope, from 14-21m). Erosion occurs up to 67% of the dune along the windward slope, with deposition (33%) concentrated at the crest of the slipface and plinth.

As with Line One, deposition over the 'depositional' area of the dune steadily increases as velocity increases. However, deposition does not decrease during Run 6 as it does on Line One. The area of maximum deposition is located at the top of the lee slope (slipface) and extending outwards at the base towards the 'plinth'. Figure 7.8 illustrates how the profiles actually changed over two days (27-29 August). The toe of the windward slope remained stationary, whilst the lee slope had advanced approximately 1.7m. The height of the dune, using the top of the slipface as a point of measurement, also increased by approximately 10cm. This increase may be due to external sediment inputs to the dune, or it may be a result of existing sediment redistribution over the dune. This process created an increasingly asymmetrical profile, which manifested itself in an increased height at the point of maximum deposition (the lee slope area), without an equal amount of erosion over the windward slope. The results presented in Chapter Five also found evidence of possible sediment redistribution. Dune height (measured at the slipface in most instances) increased as dune



# Line Two

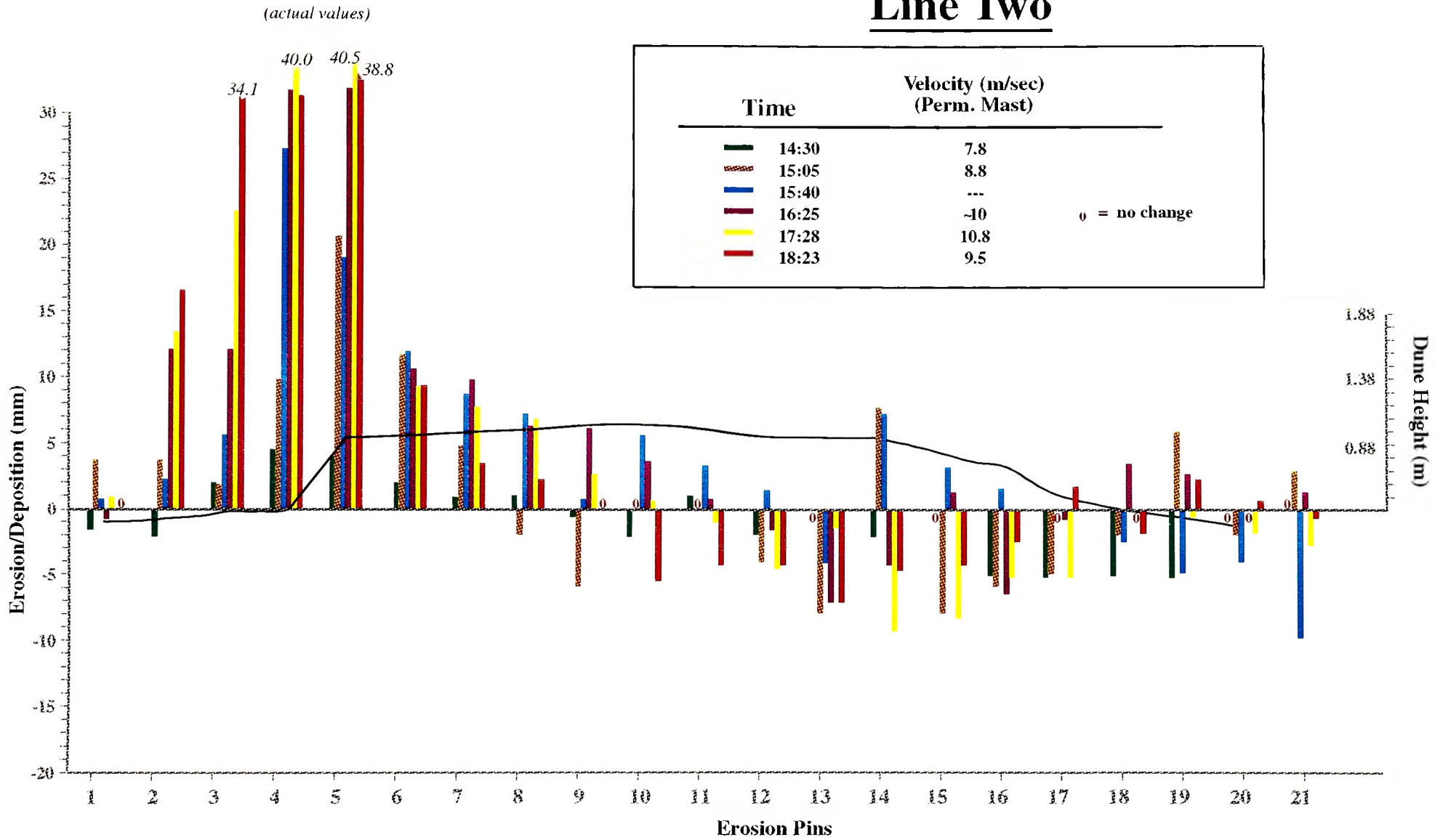


Figure 7.7 Sand transport data - Experiment One

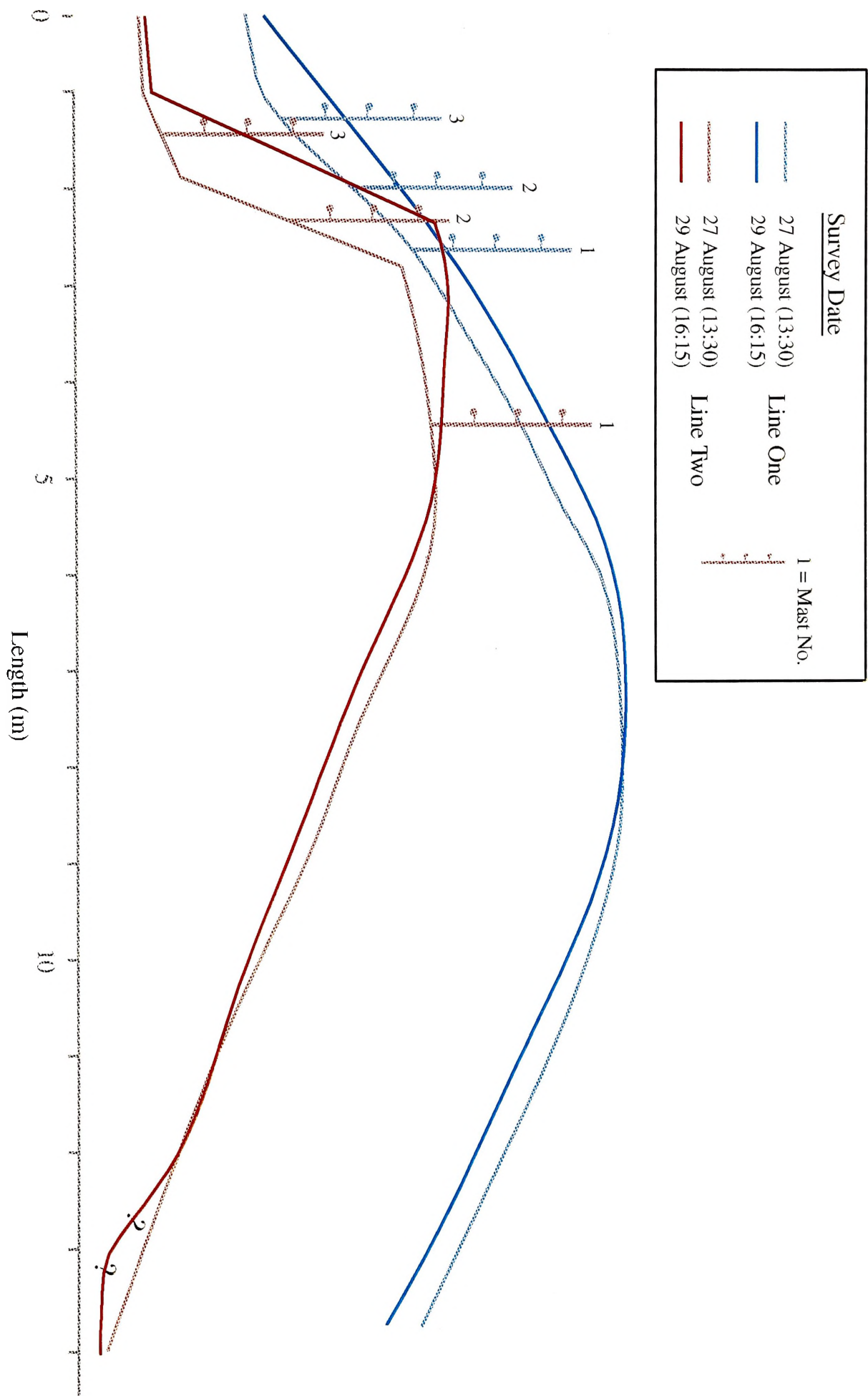


Figure 7.8 Profile change over two days - Experiment One

volume decreased, implying the dune must be assuming an increasingly asymmetrical profile in the downwind direction.

In addition to the above observations, there is a noticeable increase in deposition during Runs 2 and 4, at the base of the windward slope. It has been observed that there is commonly a decrease in wind velocity at the base of the windward slopes of low, isolated hills, and real and model dunes (Howard et al., 1978). It is expected that since sand transport is related to wind velocity, this decrease should be accompanied by a fall in sand-carrying capacity, with resulting deposition. Although the velocity patterns have been observed in nature, the expected deposition has not. It may be seen, however, that in the case of Line Two, deposition has occurred occasionally at the base of the windward slope. In the absence of velocity data, it must be assumed that velocity did decrease here, as would expected from previous observations, and that there was a corresponding episode of deposition. The results for Line One do not indicate that a similar episode of deposition occurred. This may be because the line of erosion pins did not extend out to the toe of the windward slope, and therefore were not able to measure sand transport at the same position as for Line Two.

#### 7.2.6 Summary (Experiment One)

Comparison of the velocity profiles of both Line One and Line Two indicate that flow patterns over each respective area of the dune are dissimilar. For Line One, velocity decreases at a steady rate as distance down the 'lee' slope increases. This is particularly true when permanent mast velocities are less than 10 m/sec. However, when permanent mast velocities are higher than this (Run 18), velocities measured at 250mm show a marked velocity increase. The velocity profile for Run 18 also begins to show characteristics of what may be incipient flow separation, indicating that flow velocity is an important factor in the determination of flow separation. The other velocity profiles indicate that flow separation is

not evident over this part of the dune. This is further illustrated when comparing the corresponding profiles from Line Two. Here, also, flow separation is most marked during Run 18, when overall velocities were at their highest. The occurrence of flow separation is further supported by the position of wind vanes placed in the lee area of both parts of the dune, where separation is clearly pronounced in the lee of Line Two.

Although there is no sand transport data available for Run 18, patterns of deposition and erosion seem also to be dependent on flow velocity, particularly for Line One. As velocity increases, so does deposition on the 'lee' side. Erosion, also, appears to be steady over the windward slope, compared to measurements from Line Two. Here, deposition is significantly more than that on Line One, while corresponding erosion rates are somewhat variable.

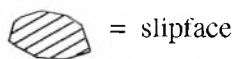
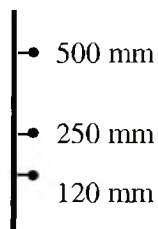
### 7.3 EXPERIMENT 2 (4 October 1989)

#### 7.3.1 Introduction

A similar experiment was conducted in October over the same dune. At this time the dune also displayed both a slipface and a non-slipfaced area. As with Experiment 1, this experiment attempted to measure and compare flow patterns and sand transport rates over an entire dune (compared to just the leeward region as in Experiment One) which displayed both a well-developed slipface and a low angle lee slope (dome).

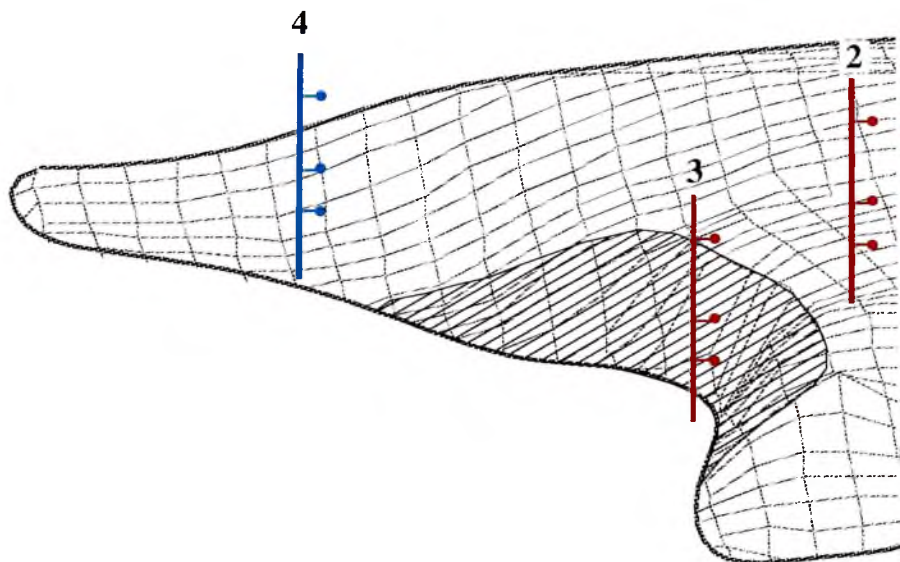
This experiment was conducted utilizing 21 anemometers on seven masts; three of these masts were loaned by the South African CSIR. The masts contained three anemometers at heights of 500, 250, and 120 mm and were placed in two lines parallel to each other across each side of the dune (Fig. 7.9). A permanent mast at 3.26m was set up on the gravel plain

Masts, with anemometers,  
with heights as shown.  
(Masts numbers are noted  
above each mast).

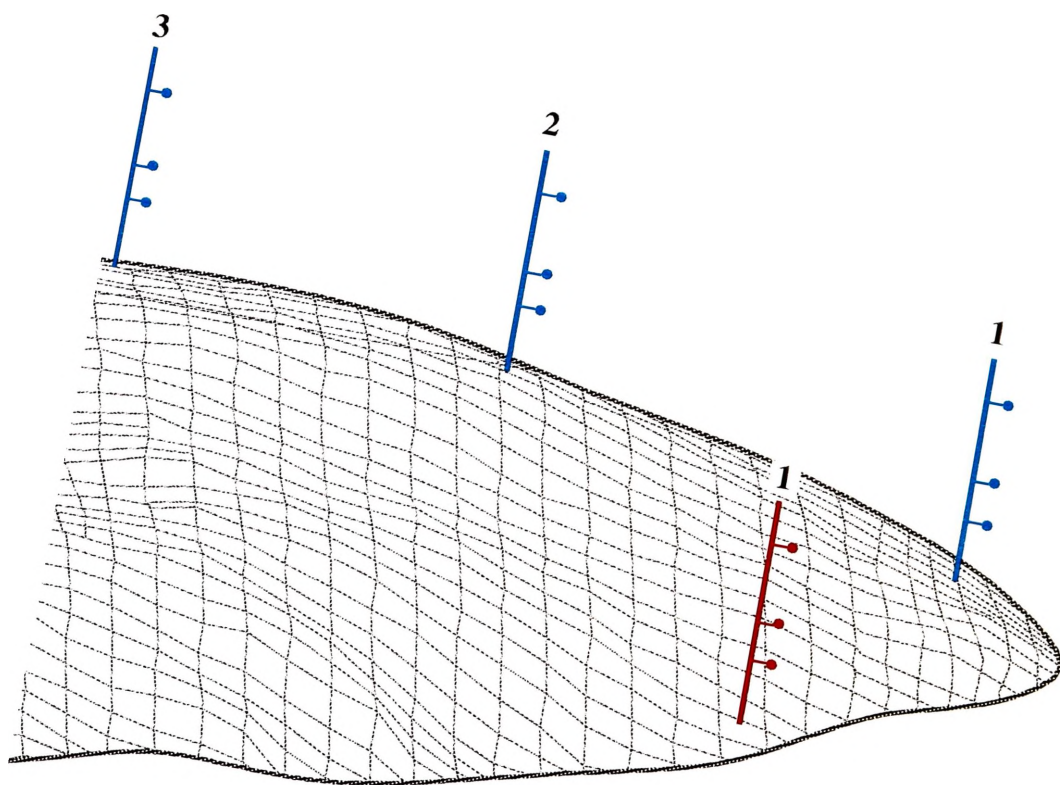


**Line One in blue**

**Line Two in red**



Note: these positions and heights are not to scale.  
The positions of both the anemometers and  
the masts are approximate only.



**Figure 7.9** Location of masts - Experiment Two

approximately 50m to the north of SW1. Line One (the area with no slipface) contained four masts positioned along the long axis of the dune, starting from the front (northern) edge of the dune and back towards to the toe of the windward slope. Line Two contained three masts which were positioned at the base of the slipface, the crest of the dune, and at the windward edge. Velocity readings were taken at two-minute intervals, for a total of nine runs.

Erosion pins were positioned along both lines (Fig. 7.10). Line One contained 13 pins, whilst Line Two had a total of eight. The pins were set at a height of 500mm at 16:48 and subsequent height readings were taken every thirty minutes until 18:18. The erosion pins were left in place at the conclusion of the flow experiments. On 7 October (9:00) a pin height reading was taken. Further pin readings were taken on 9 October at 10:30 and 15:40. These readings are useful for both short-term sand transport calculation, i.e. for 1.5 hrs as on 4 October, and for medium term sand movement using the initial reading and calculating erosion/depositional change over the entire 5-day monitoring period.

### 7.3.2 Velocity Profiles (Line One)

Line One contained four masts each with three anemometers, aligned parallel to the long axis of the dune (Fig. 7.9). Wind flow experiments commenced at 17:12 and concluded at 18:44.

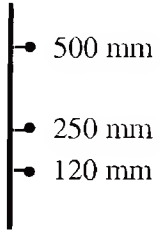
Although there were differences in wind velocities for the anemometers, over several runs these differences were not highly significant. Mast One velocities were slightly higher than those for Mast Four, whilst the anemometers on Masts Two and Three exhibited very similar velocities. These results are not surprising, given the results of previous work on the flow patterns over low hills (Hunt and Snyder, 1980; Mason and Sykes, 1979). Figure 7.11 shows wind observations over a low hill, with the arrows indicating measured wind velocities and directions over several areas of the dune. The velocities tends to gradually



Masts, with anemometers,  
with heights as shown.  
(Masts numbers are noted  
above each mast).



slipface



500 mm

250 mm

120 mm

Line One in blue

Line Two in red

erosion pin  
Line One

erosion pin  
Line Two

Note: these positions and heights are not to scale.  
The positions of both the anemometers, masts,  
and erosion pins are approximate only.

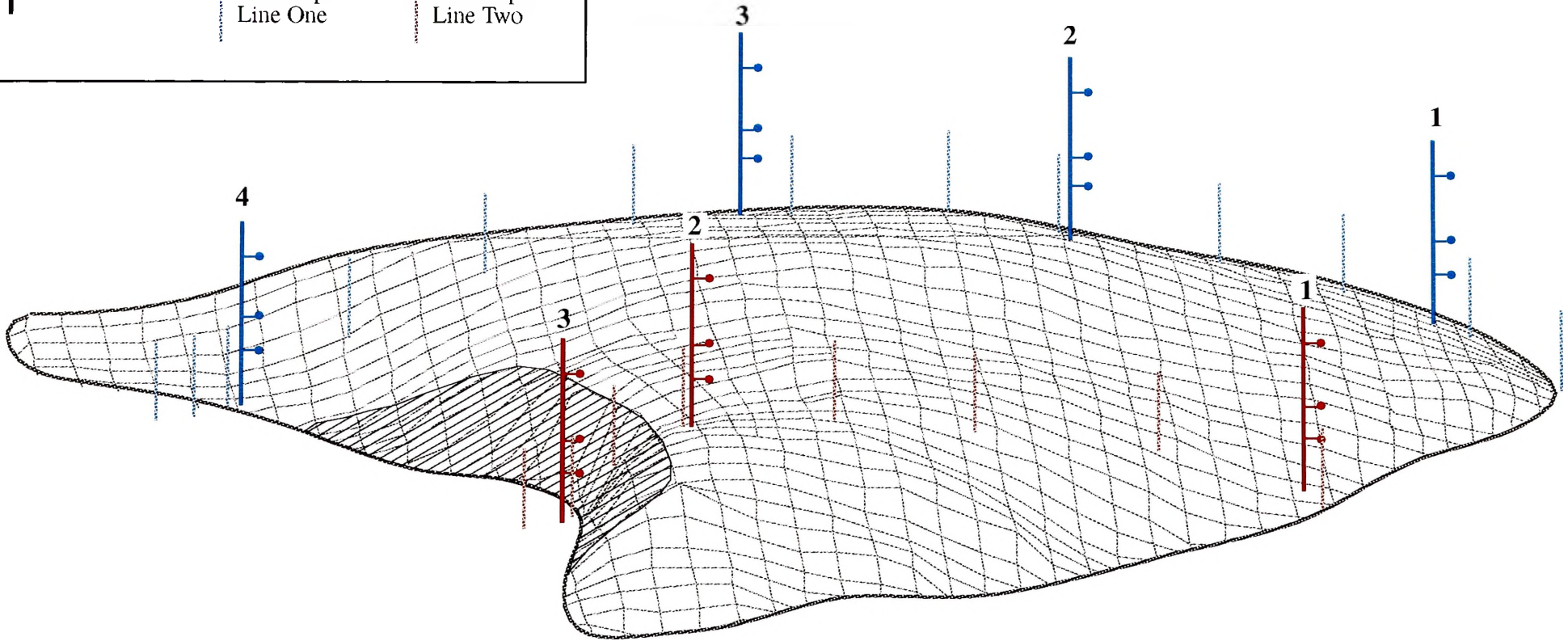
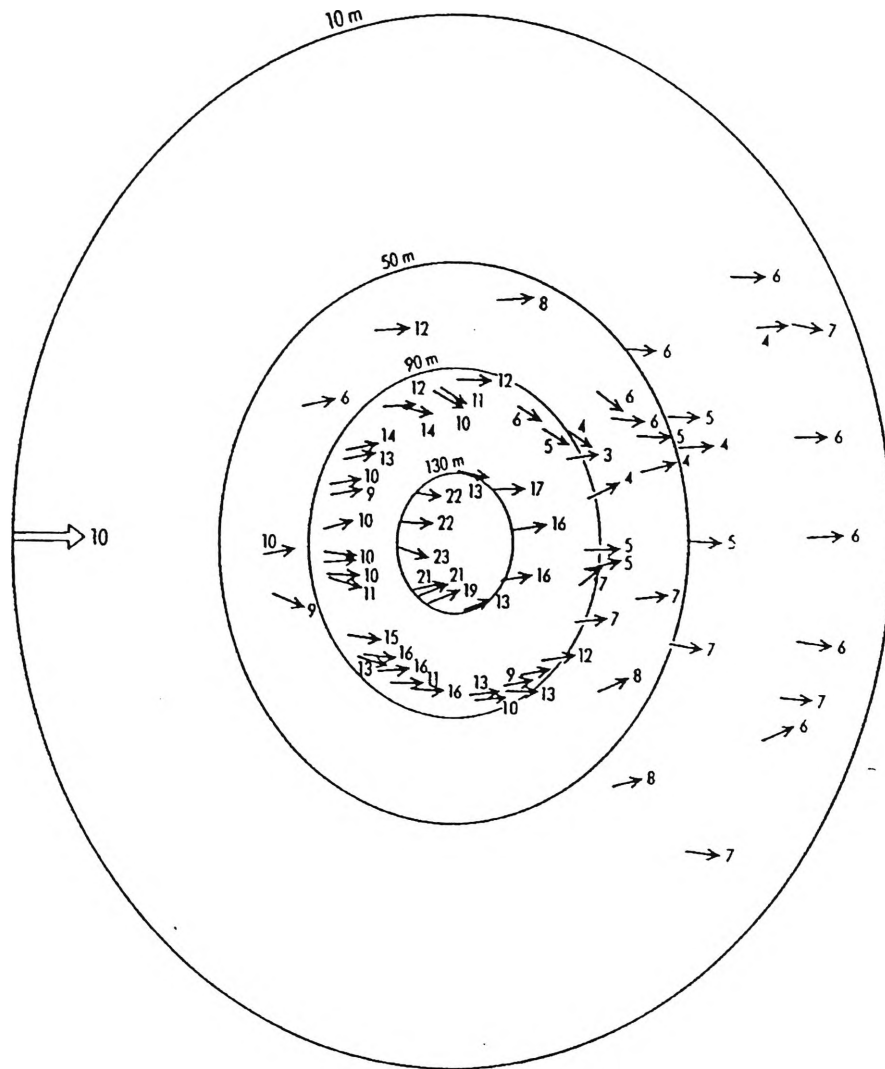


Figure 7.10 Location of masts and erosion pins - Experiment Two





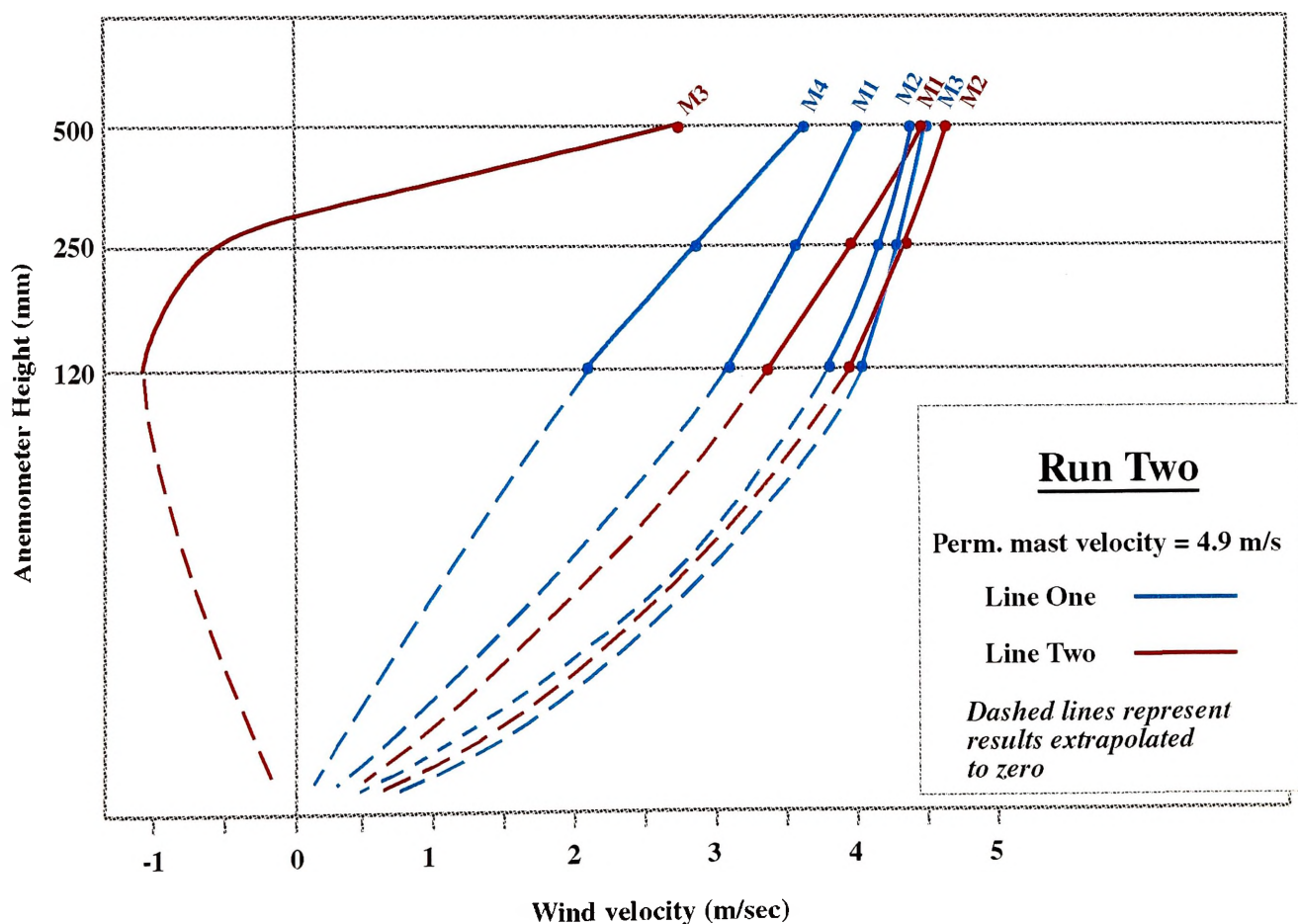
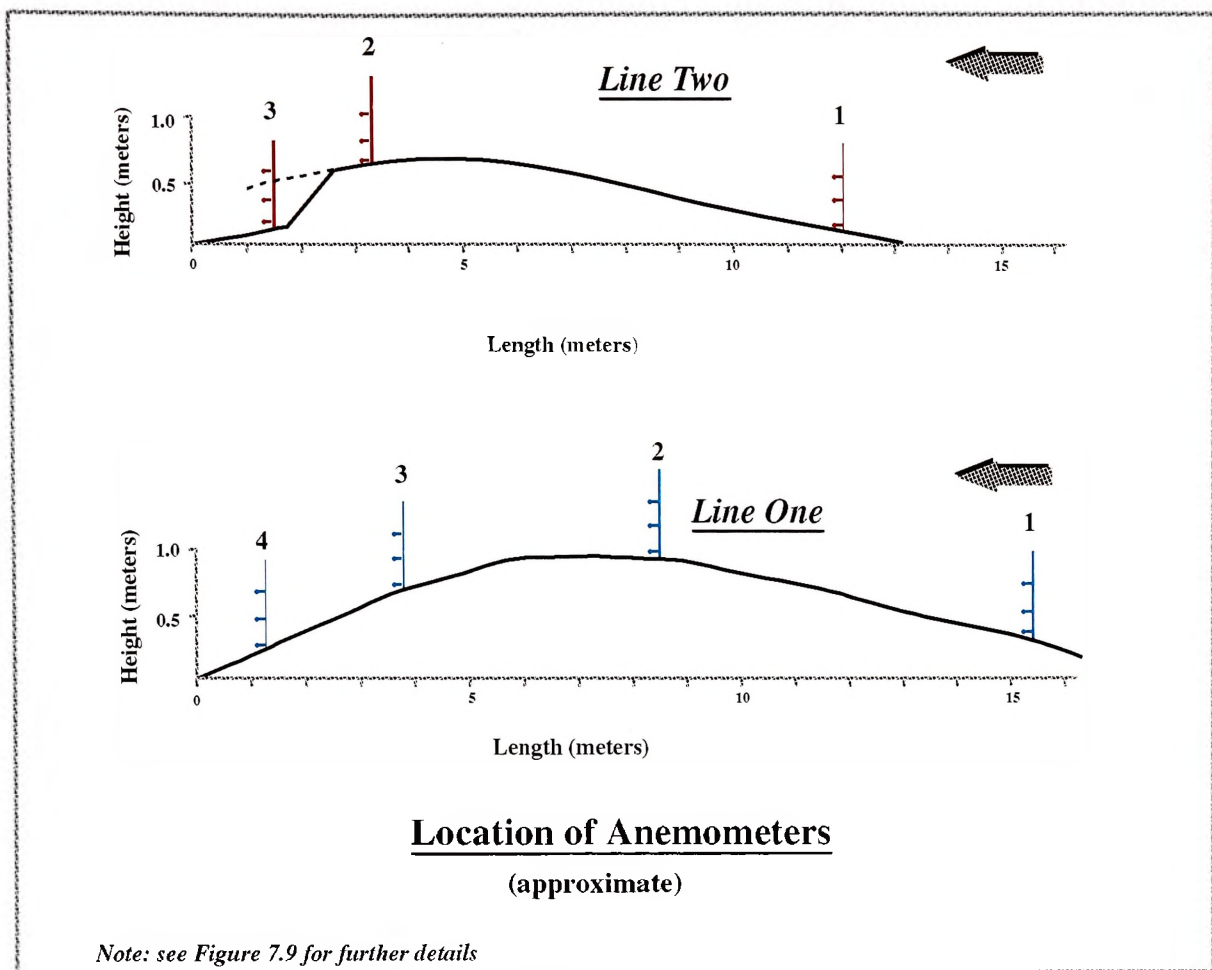
**2m wind observations on and around Brent Knoll. Wind speeds in m/s are indicated on the arrows (from Mason and Sykes, 1979).**

**Figure 7.11 Flow patterns over a low hill**

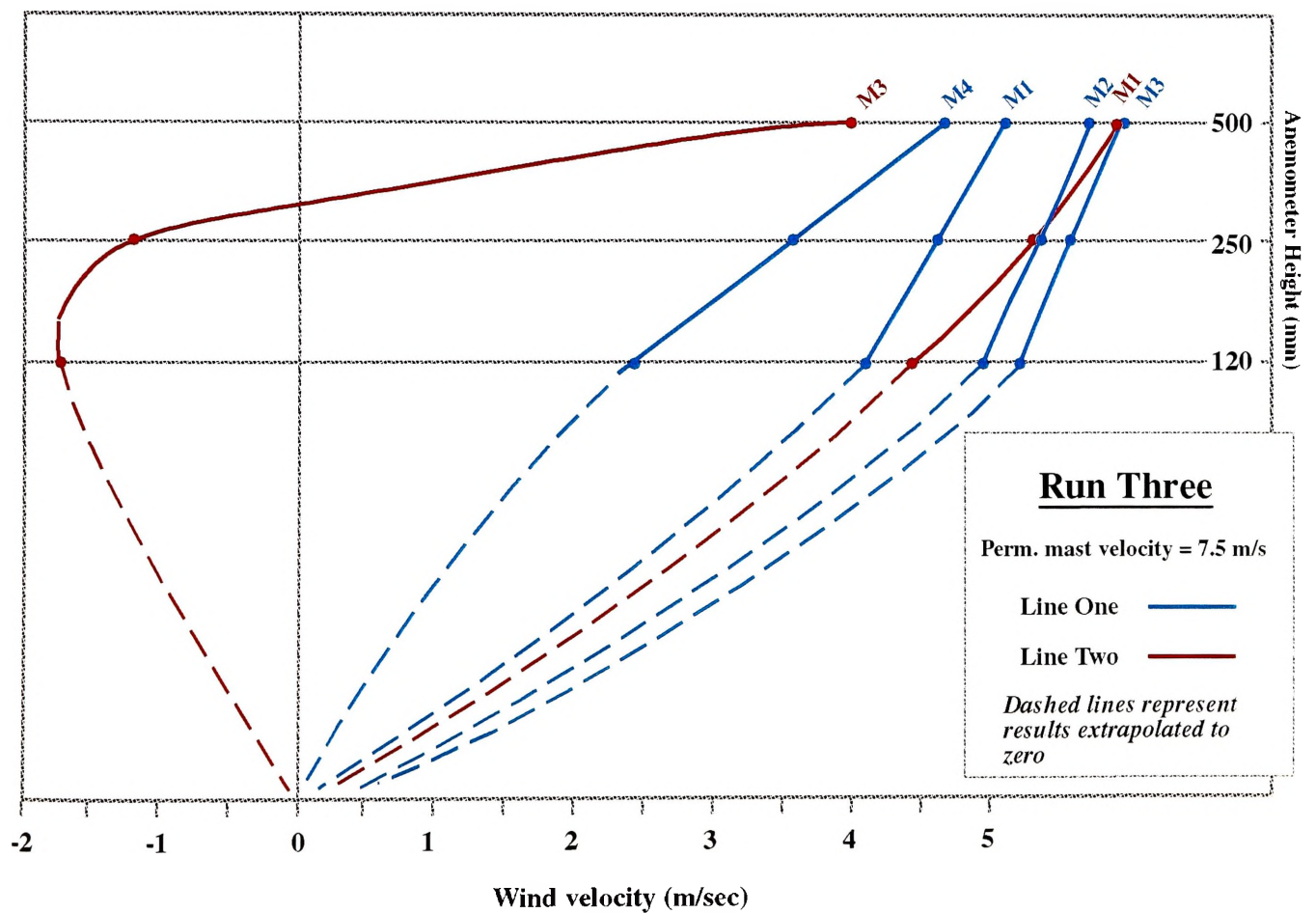
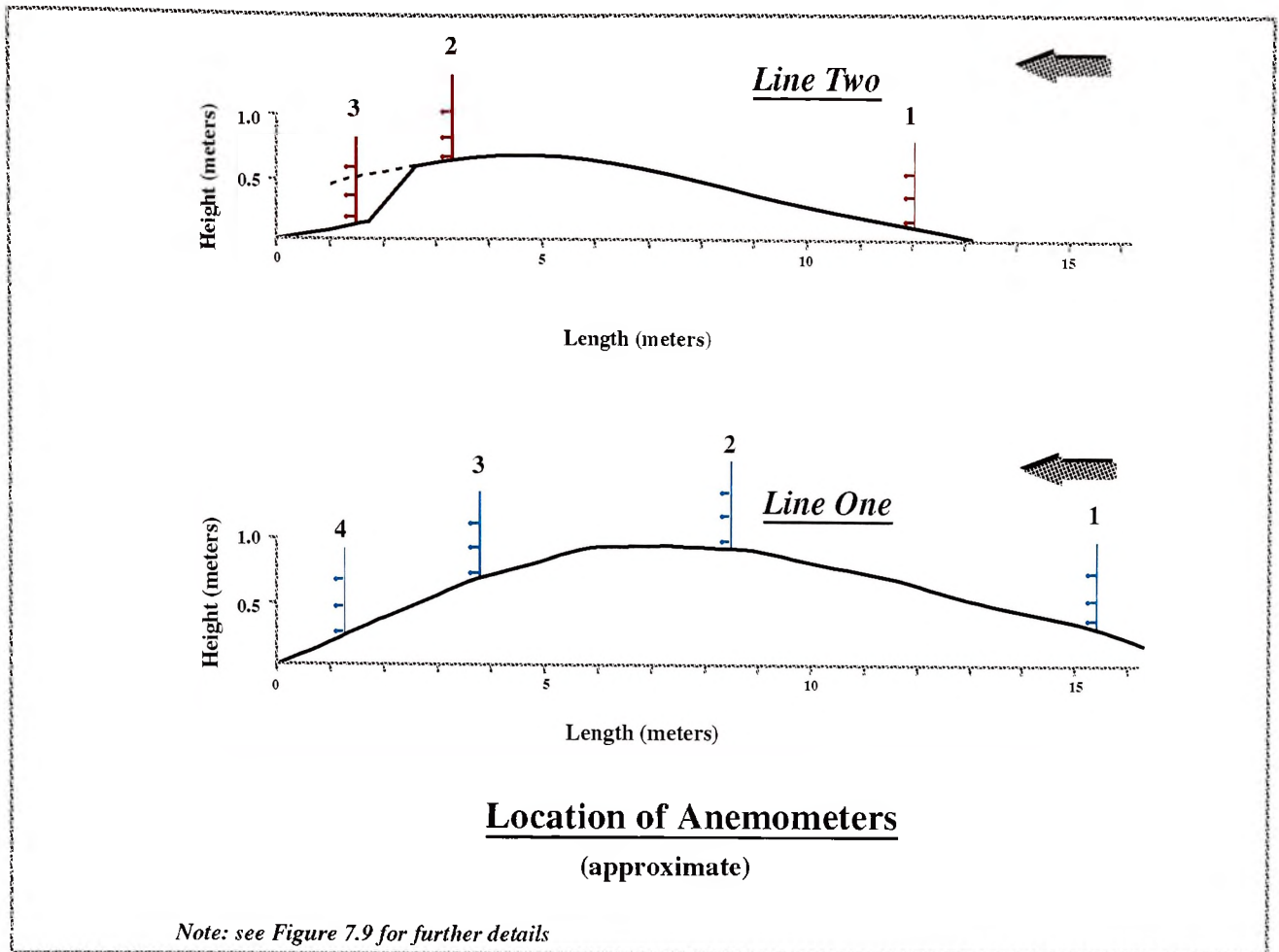
increase from the 'toe' of the hill to the crest, where they increase significantly. They then decrease with distance down the 'lee' slope, and eventually the velocities are less than those measured on the windward slope. This pattern is also exhibited in the velocity profiles for Line One. The anemometers on Mast 4, located at the base of the lee (downwind) slope, show the lowest measured velocities for all runs (Fig. 7.12 and 7.13), while the anemometers on Mast 3, near the crest of the dune, exhibited the highest velocities. Mast 1, at the base of the windward slope, shows the second lowest wind speeds.

The velocities for all masts reflect variations in the permanent mast velocity. Unfortunately, no permanent mast velocity was recorded for Run 1; however, results for both Run 2 and Run 3 show that with the higher permanent mast velocity (7.5m/sec for Run 3), all recorded velocities are higher. In addition, the velocity gradient is steeper at the higher permanent mast velocity, particularly for Mast Four. Here, the anemometers at 12cm do not show significant differences in velocities. Mast Two and Mast Three anemometers, at the lower permanent mast velocity, show little variation between the 12cm and 50cm anemometers, unlike the results for the higher velocities (Run 3) where the differences are greater. With the higher ambient velocity, speed-up over the crest is increased. This is also demonstrated when Runs 2 and 3 are compared. At 7.5 m/sec winds, the Mast Three anemometers exhibit higher velocities than those for Mast Two. This is not the case at the lower velocity (4.9 m/sec permanent mast for Run 2) where the difference between Mast Two and Mast Three velocities are somewhat less, particularly at the 10cm and 50cm level.

No evidence of flow separation or reversal exists in these profiles and the wind vanes utilized in this experiment did not indicate flow reversal. There is a steady velocity increase (speed-up) upslope and then a steady incremental downslope decrease with distance downwind, as with Experiment One.



**Figure 7.12 Velocity profiles - Experiment Two**



**Figure 7.13 Velocity profiles - Experiment Two**

### 7.3.3 Velocity Profiles (Line Two)

Due to technical difficulties, some anemometers did not operate on some runs. Thus, in Figure 7.13 (Run 3), the Mast Two velocities are absent.

Figure 7.12 and 7.13 show the velocity profiles across the slipface portion of the dune (Line Two). The anemometers positioned on Mast 2, located near the crest of the dune, measure the highest overall velocities, while those on Mast 3, at the base of the slipface (120mm), measure the lowest. As in Experiment One, the results indicate that wind flow accelerates up the windward slope and then separates as it passes over the brink of the slipface. The extent of the flow separation increases as wind velocity increases, as evidenced by the comparison between Run 2 and Run 3.

### 7.3.4 Line One and Two Compared

A comparison of velocity profiles for Lines One and Two indicate that the degree of flow separation is velocity-dependent; a higher velocity will produce a greater degree of flow separation, as demonstrated in Experiment One also. As velocity increases over a low slope with no slipface (Line One), measured flow on the 'lee' side of the dune appears to trend towards flow separation, i.e. the profile develops a slight concavity as the measured velocities decrease down the profile, while maintaining higher velocities at the 50cm level. That separation and subsequent slipface development was possibly imminent is further supported by the fact that the dune contained a grainfall zone, which continued to develop over the period 4-9 October.

Grainfall zones were defined in Chapter Six as areas along the lee face of the dune where ripples end and minor deposition becomes noticeable. Grainfall zones are smooth, relatively

low-angle slopes which are quite distinct from slipfaces. Because these zones are generally at the downwind end of rippled lee faces, the existence of these zones may imply a change in wind velocity, flow structure, and/or sediment transport mechanism. The slight concavity of the velocity profiles presented here (Line One, Mast Four) indicate that a slight reduction in wind velocity did occur, and may indicate that over time this slope may develop further into a slipface, particularly since a slipface was already present at the other side of the dune.

As velocity increases, or maintains a minimum threshold, and flow is unidirectional over time, then a slipface will tend to develop. The survey results of 7 October show that this grainfall zone had continued to develop over the Line One area, as mentioned earlier in this section. However, the length of the slope remained over twice that of Line Two, implying that flow characteristics, i.e. velocity and direction, must be the primary controlling factor in slipface development. This implication appears even more plausible upon further examination of the wind data for both Salt Works and Kleinberg weather stations. From the 4-7 October, the data indicate that wind direction was primarily WSW, and ranged in velocity from 4 to 9 km/hr (Kleinberg) up to 14 km/hr at Salt Works. This direction, which is parallel to the dune axis, remains reasonably consistent (WSW to southwest) over the 3-day period between the experiment and the survey. These results appear to indicate that slope length is a secondary factor in slipface development; over time, higher uni-directional velocities will ultimately result in slipface development, irregardless of slope length.

The following sections will incorporate sand transport data with measured flow velocities to further establish the relationship between velocity, flow separation, and slipface development.

### 7.3.5 Sand Transport (Line One)

Erosion pin measurements were taken at regular intervals during the wind flow experiments. Since the experiments only ran for 1.5 hours and wind velocities were fairly low, sand transport was variable over the experimental period (Fig. 7.14a-d). As a result, the pins were left in place until 15:40 on 9/10/89. Measurements were taken at 9:00 on 7/10/89, and 10:30 and 15:40 on 9/10/89. Dune profiles and erosion/deposition graphs were drawn for the period 4/10/89 (commencement of measuring) to 7/10/89, and from 7/10/89 to 9/10/89 (Fig. 7.14a-c). Erosion and deposition graphs and profile change was also drawn for the entire measuring period (4/10/89 to 9/10/89) (Fig. 7.14d).

As with the previous experiment, a definite zone exists where erosion ceases and deposition begins, although this is not apparent during the time of the velocity experiments where velocities were low. The trend becomes more noticeable after the 7/10 measurement is made (Fig. 7.14b). The rate of erosion seems to virtually equal the rate of deposition. Erosion occurs over 55% of the dune length, with deposition (45%) concentrating near the lee slope of the dune. Comparing these percentages to the sand transport patterns for the period 7/10 to 9/10 (10:30) (Fig. 7.14c), a small amount of deposition is noticeable at the base of the windward slope, but deposition has increased significantly over the lee slope. Erosion is concentrated near the crest of the dune and up the windward slope. This area represents 46% of the total dune length.

The deposition which occurred at the base of the windward slope provides further evidence of a reduction in velocity and hence carrying capacity which occurs across the windward slope. As discussed in section 7.2.5, this deposition has been hypothesized but never previously observed in the field. Velocity data obtained from Mast One, near the base of the windward slope, indicate lower velocities which increase with distance up the windward



Time of Survey

— 16:48 (4/10)

- - 18:18 \* (4/10)

\* no measurement is shown, as  
the profile change over this  
time period was not significant

Deposition  
Erosion

Line One

Dune length (m)

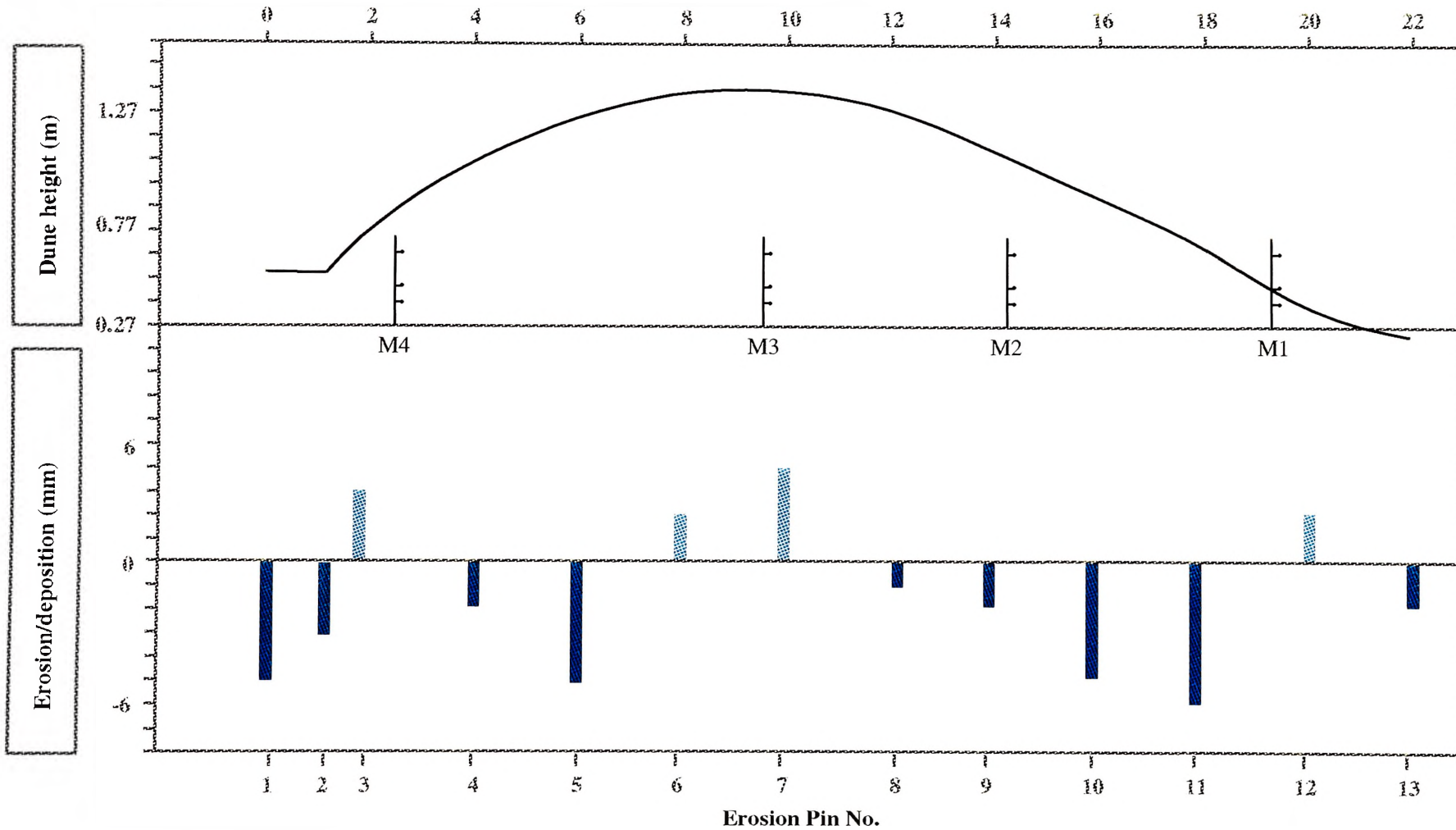
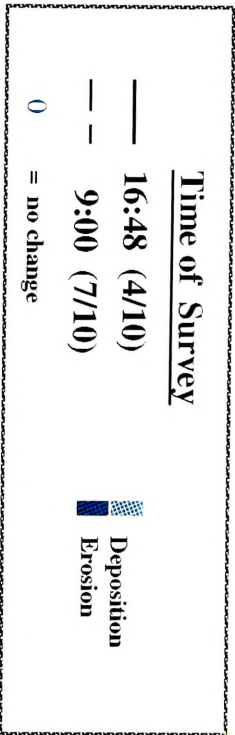


Figure 7.14a Erosion and deposition - Experiment Two





# Line One

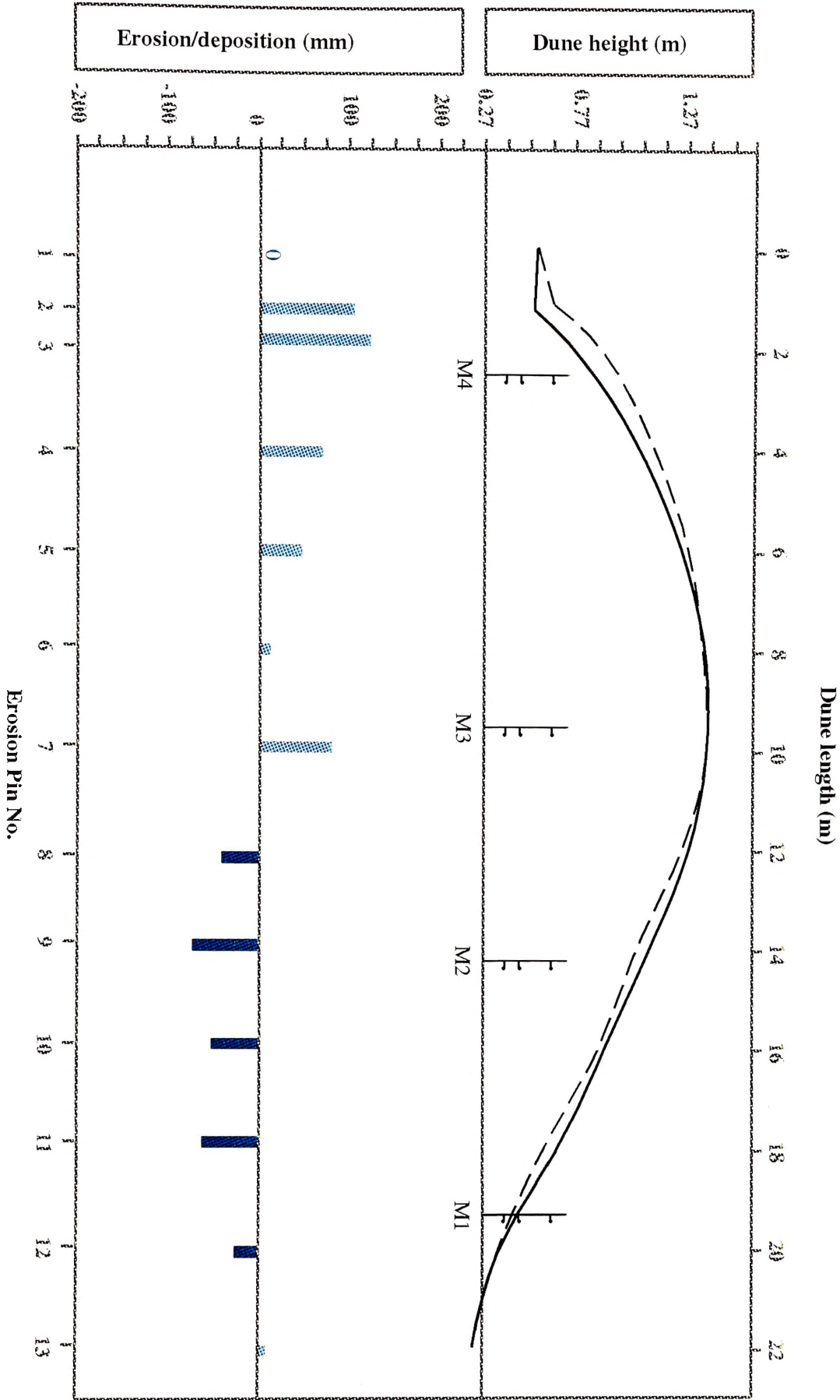


Figure 7.14b Erosion and deposition, Experiment Two

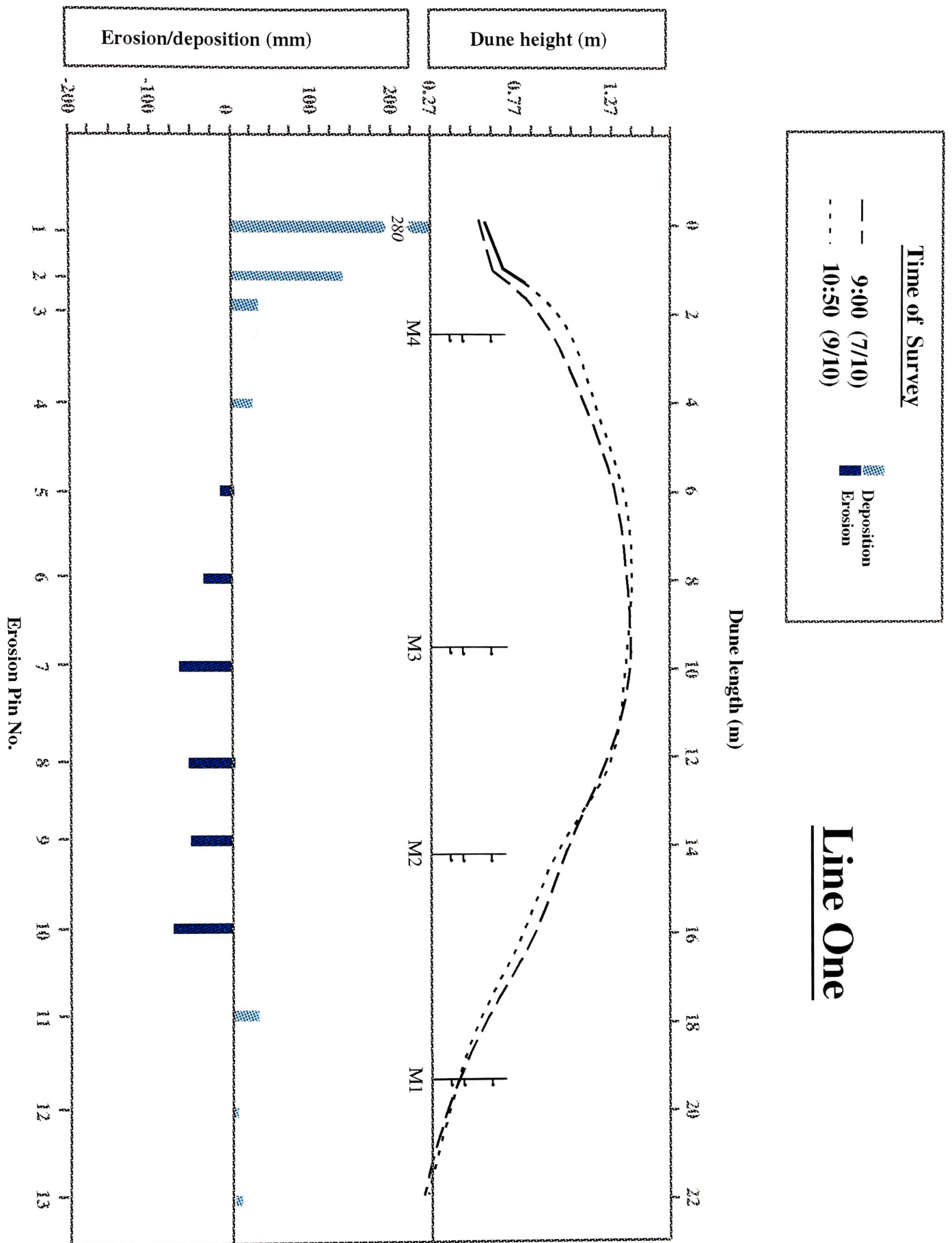
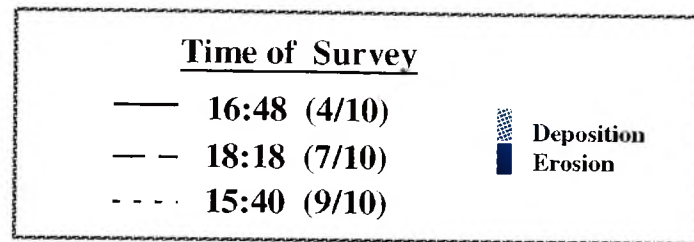


Figure 7.14c Erosion and deposition, Experiment Two



## Line One

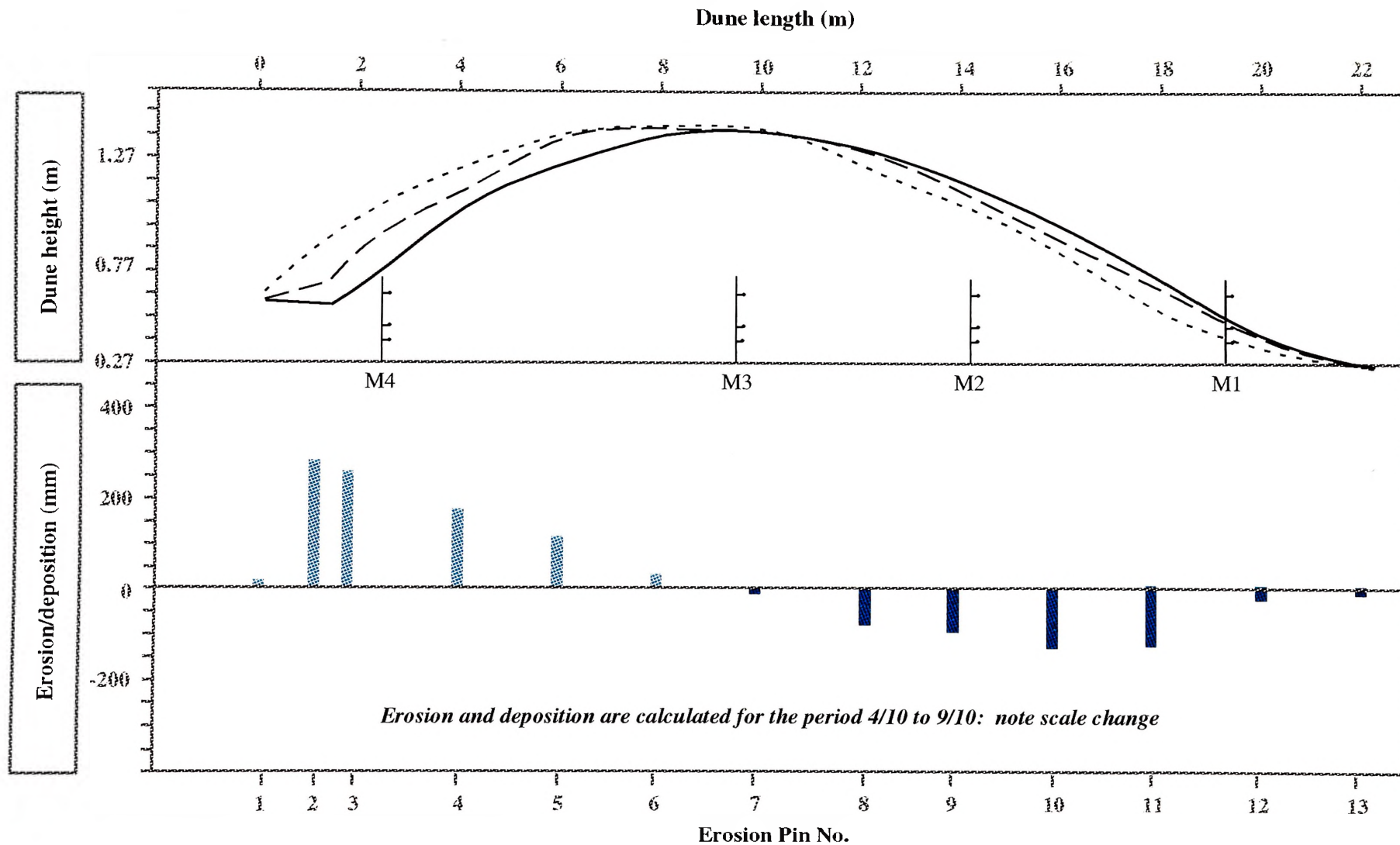


Figure 7.14d Erosion and deposition, Experiment Two

slope and over the crest. These results are consistent with the measured depositional patterns (Figure 7.14a-c).

Figure 7.14d shows the profile changes and sand transport patterns for the entire period (4/10 to 9/10). As with previous measurements, erosion is concentrated along the windward slope, with deposition occurring only over the lee slope downwind of the 'dome' crest. Erosion occurs over 59% of the dune length, with the 'transition zone' located at or near the highest point on the dune. Although erosion occurs over approximately half of the dune area, quantification of erosion pin data (the amount of sediment accretion or deposition in millimeters) indicates that only 38% of the total amount of transported sediment is located within this erosion zone, while 62% of the sediment lies within the depositional zone, an area representing only 41% of the dune area.

Overall dune length did not increase, despite changes in the dune profile. The changes occurred mainly on the lee slope. The lee slope angle increased slightly, while the windward slope angle showed little change over the same period (Fig. 7.15). Measurement of the slope angles from commencement of the experiment to the end indicate that slope angles in actual fact change little from 4/10 to 9/10. Lee slope angles are between  $8^{\circ}$  and  $10^{\circ}$ , while windward slope angles all measure  $5^{\circ}$ . Although these changes are minimal, the overall dune profile becomes steadily steeper and flatter, as it must since the overall length has changed only slightly. Should this process continue, it is inevitable that a slipface will develop, as the lee slope oversteepens and avalanching occurs.

Although minor steepening of the lowest portion of the lee slope angle is apparent, due to sand accretion, advancement of the dune is not significant. If the base of the grainfall zone is defined as the base of the dune at Line One, total movement is approximately 1.2m, compared to 2m for Line Two. It may be seen from erosion pin data along Line One that

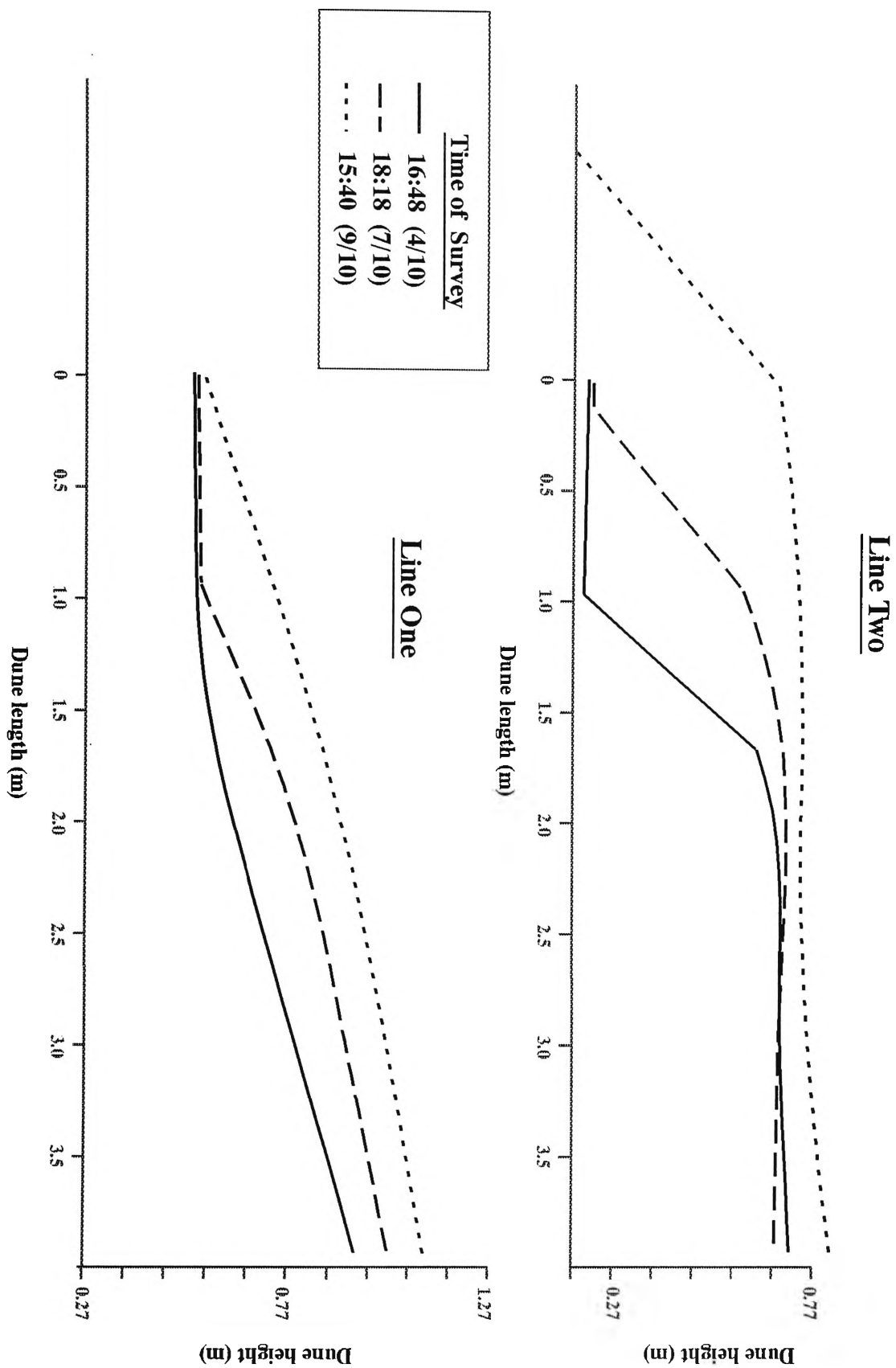


Figure 7.15 Lee slope profile change - Experiment Two

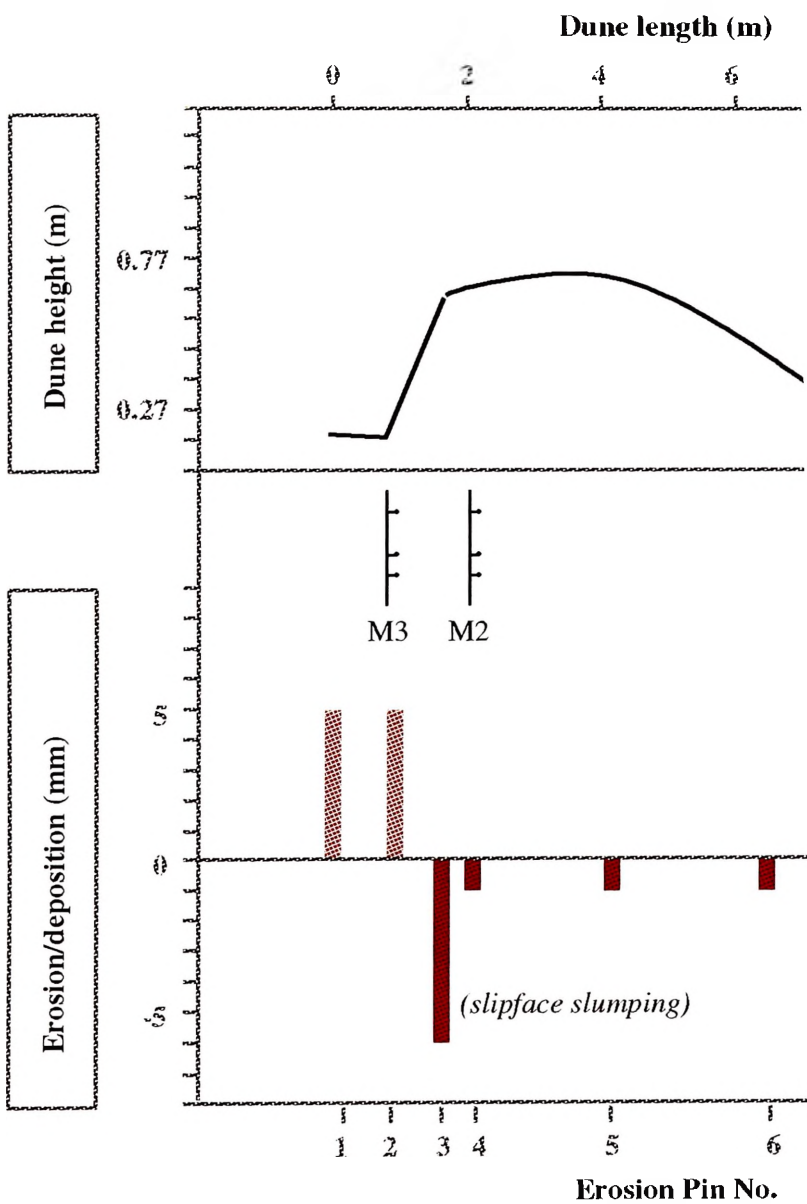
vertical accretion of sediment occurred at the base of the dune on the lee side up to the crest, as evidenced by the net accumulation of sand at Pin 1 through Pin 6. This may be loosely construed as forward movement, but is not nearly as pronounced as that which occurred over the same period along Line Two.

### 7.3.6 Sand Transport (Line Two)

As with Line One, several graphs showing erosion and deposition were drawn for a variety of time periods. (Fig. 7.16a-c). The measurements taken on 4/10 show little profile change, although deposition was quite definitely concentrated on the lee slope unlike Line One where, over the same period, erosion and depositional patterns were highly variable during the flow experiment. Between 16:48 on 4/10 and 9:00 on 7/10, the dune had advanced approximately 0.9m (Fig. 7.16b). The depositional zone had lengthened to equal 25% of total dune area, with most of the sand accretion occurring along the middle of the slipface.

### 7.3.7 Summary (Experiment Two)

The velocity profiles for Experiment Two indicate that flow separation is velocity-dependent. Hoyt (1966) also observed that the stronger the wind, the stronger the lee eddy (separation envelope) development. As the permanent mast velocity increased, the degree of flow separation occurring over Line Two increased. Deposition over the lee slope resulted from this velocity decrease. Increasing profile asymmetry over the slipfaced area of the dune was evident from 4-9 October, as the lee slope continued to be an area of high deposition. Since the toe of the windward slope did not change, sediment redistribution was inevitable, with the lee continuing to steepen as a result of the high deposition. Dune height increased only marginally over Line Two, but remained constant for Line One (Fig. 7.15). A grainfall zone existed at Line One at the onset of the experiment, and continued to develop. However, a



# Line Two

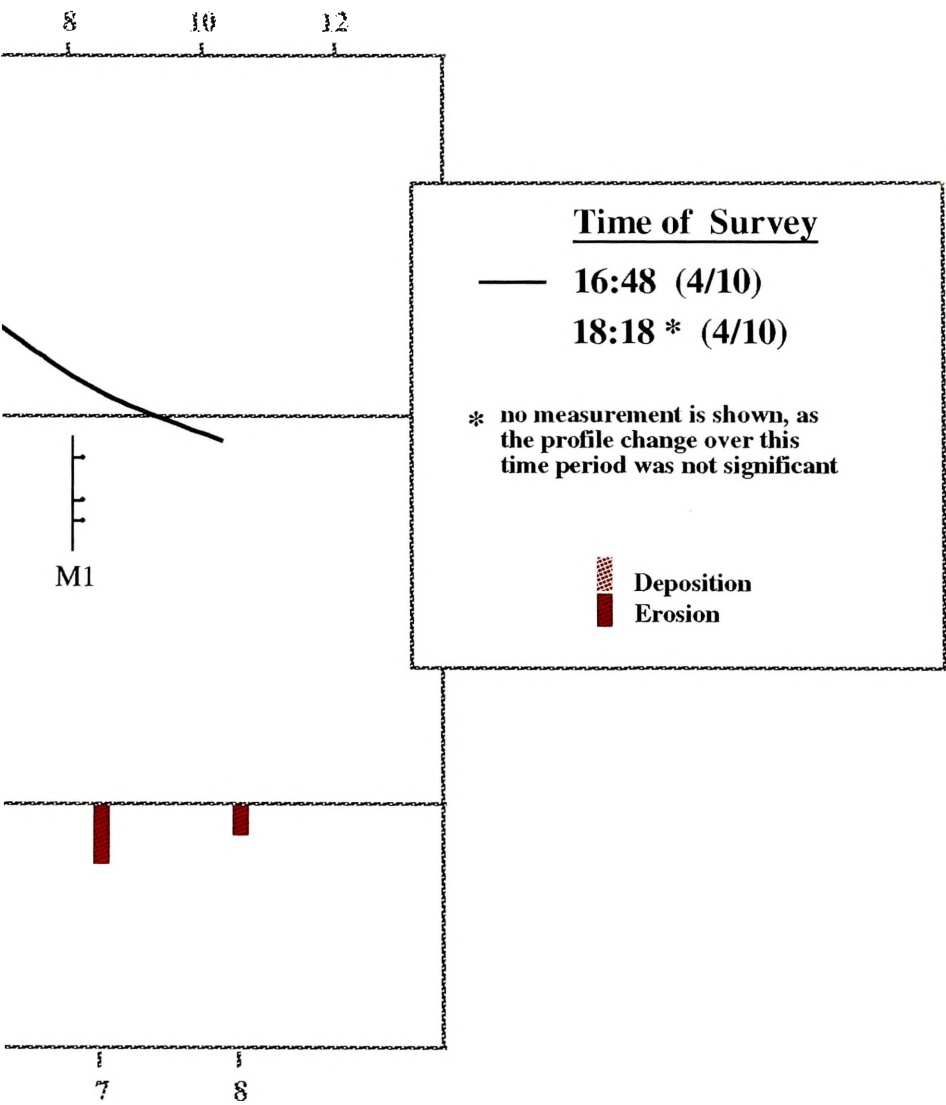
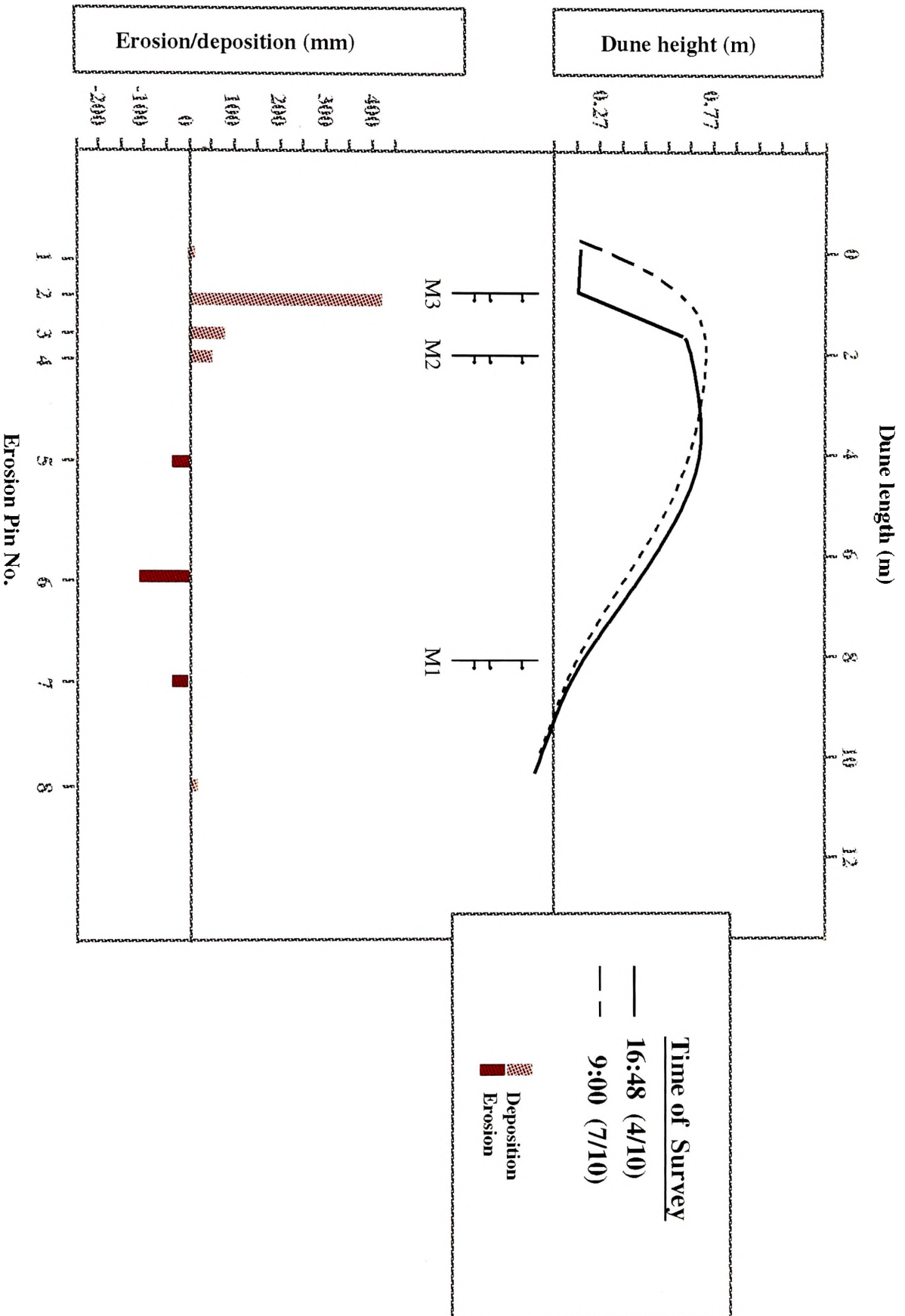


Figure 7.16a Erosion and deposition patterns for a minimum period, Experiment Two



## Line Two



**Figure 7.16b Erosion and deposition patterns over three days, Experiment Two**

# Line Two

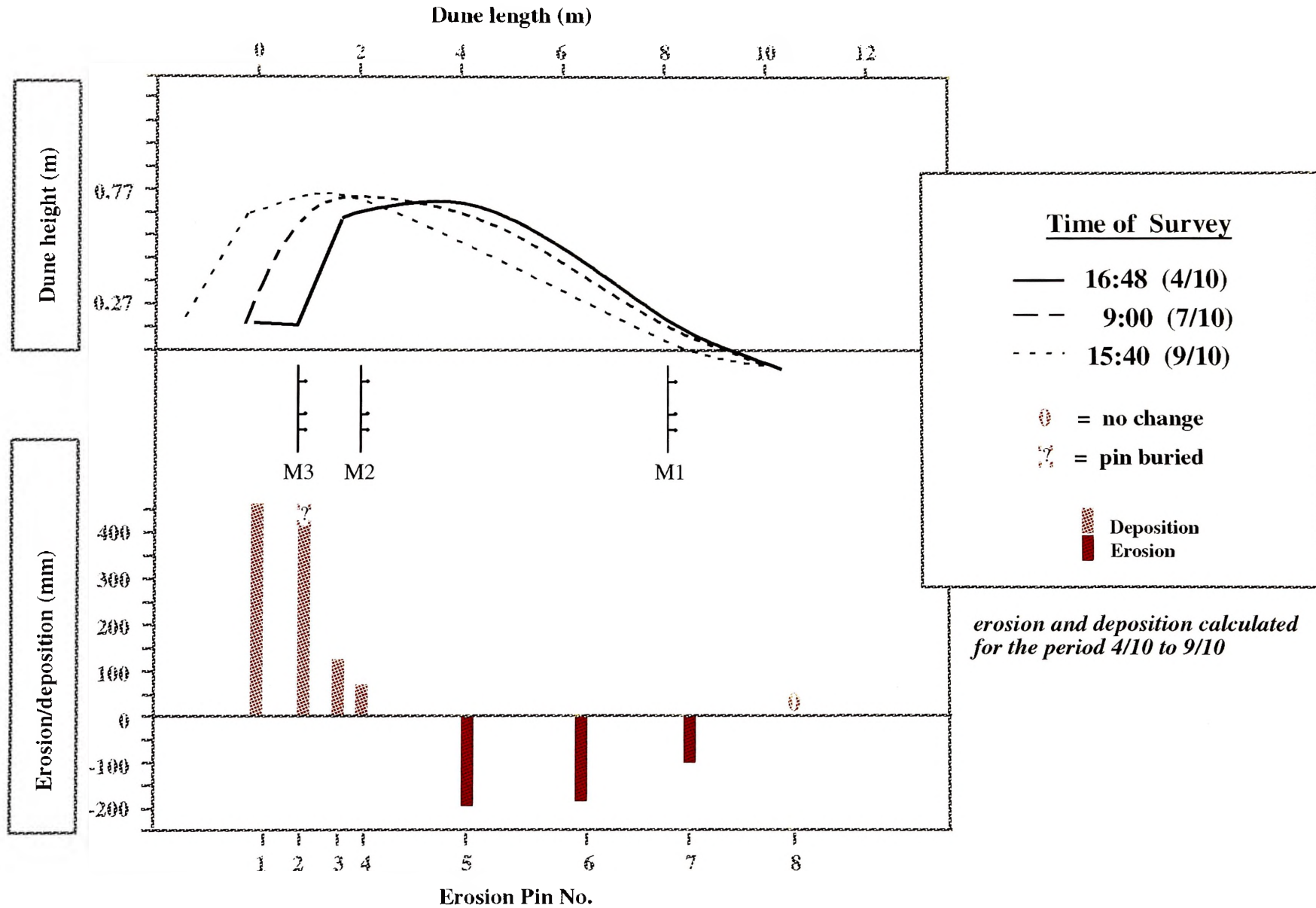


Figure 7.16c Erosion and deposition patterns over five days, Experiment Two

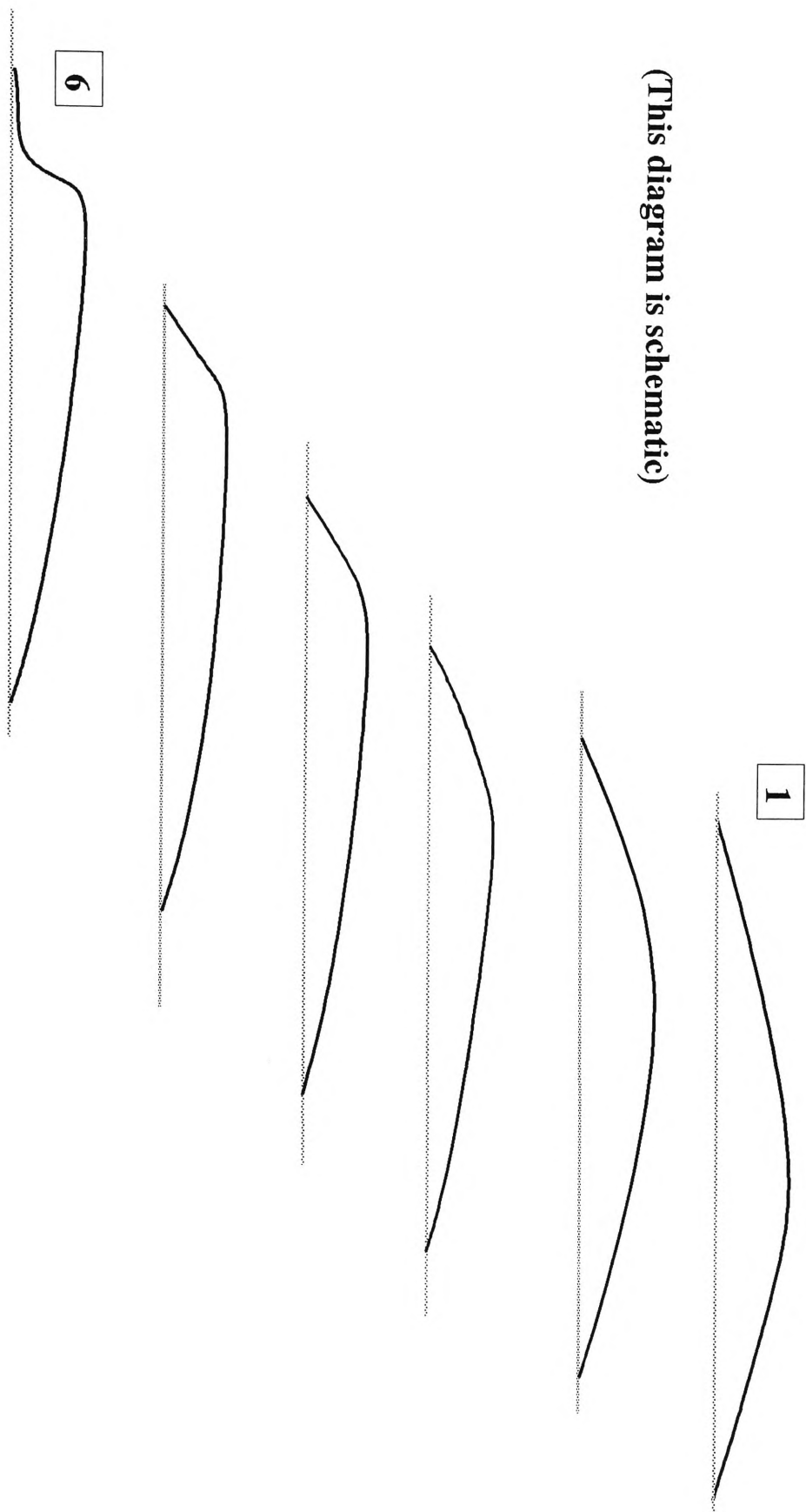
slipface never formed, despite the slight steepening and increased deposition over the lee slope.

Two possible explanations exist for this lack of slipface development within the first survey time; firstly, a change in wind direction. The final survey of this dune was done on 23 October. At this time there was no evidence of either a slipface or a grainfall zone at Line One, implying that wind conditions must have changed (Line Two continued to have a well-developed slipface, although it was much smaller in area). Secondly, a decrease in overall wind velocity may have suppressed the development of a slipface, particularly if this decrease were accompanied by a change in direction.

#### 7.4 HYPOTHESIS OF DOME - BARCHAN EVOLUTION

A preliminary hypothesis, based on the results of Experiment One and Two, may help to explain the sand transport patterns observed. A proportion of sediment is eroded from the area located just past the base of the windward slope, where maximum erosion was shown to occur (Fig. 7.7). Velocity then compresses and accelerates, resulting in maximum transport up the dune windward slope. Flow separation over the slipface is linked to this process; flow decompresses and decelerates (separates) just past the highest point on the crest as pressure drops, resulting in deposition as carrying capacity is reduced. This trend continues over the slipface.

These changes in flow behaviour are accompanied by adjustments in the dune profile (Fig. 7.17). At the onset of measurement, the dune was relatively symmetrical in form, i.e. dome-like. Given a steady wind velocity, over time this form gradually assumes an increasingly asymmetrical profile, as erosion continues on the windward slope, and relative deposition increases over the downwind edge, or lee slope, of the dune. Figure 7.17 illustrates these



**Figure 7.17 Schematic diagram showing profile evolution from a dome to a barchan**

changes. As the process continues, the profile gradually steepens, with minor flow separation becoming evident as the dune height increases. This flow separation facilitates the steepening and eventual failure of the lee slope, which ultimately results in an 'incipient' slipface at the crestal area of the dune. Continuing flow acceleration and sand transport, followed by sudden deceleration (separation) and deposition, allows this 'incipient' slipface to evolve into a fully developed slipface. This slipface is maintained over an indefinite period of time, unless external factors, specifically wind velocity and direction, and sediment supply, upset the balance, or 'equilibrium' of the dune form. These factors and their effect on dune morphology are discussed in the following section.

#### 7.4.1 Equilibrium Profiles

If the idea of 'equilibrium' profiles is addressed, in light of the sand transport data and the velocity profiles from Experiment One and Two, only the non-slipfaced part of the dune represents an equilibrium form. In Chapter 4, an equilibrium form was defined by Yalin (1977) as one that produced the smoothest flow and thus equalized energy loss in the streamwise direction. In the context of sand transport and streamlines, an equilibrium profile is one where erosion is reasonably equal to deposition, and velocity profiles (streamlines) follow the contour of the dune shape, with no streamline disturbance. From this definition, it may be assumed that a disruption in the erosion/deposition balance will result in a 'disequilibrium form'.

Changes in wind velocity and direction, and variations in sediment supply represent external factors which may potentially disrupt the erosion/deposition balance. Increasing wind velocity affects dune evolution in two significant ways: firstly, changes in velocity, providing they are not accompanied by changes in direction, will affect the rate of change. Assuming that wind velocity is above threshold, the profile changes illustrated in Figure 7.17 will occur

over time; however, if wind velocity is increased substantially, the rate at which these changes occur is also increased. Secondly, it has been shown in Experiment One and Two that increased wind velocity leads to a higher level of flow separation (Fig. 7.5). Flow separation acts as a catalyst for increasing sediment deposition near the crest and, ultimately, slipface development.

In addition to flow velocity, direction is also important. A change in flow direction results in dune morphologic re-adjustment, as illustrated in Chapter Six. In areas where unidirectional wind regimes occur irregularly, or where a bi-directional wind regime is predominant, a dune is often in a prolonged 'transitional' state of re-adjustment, which may be equated with 'disequilibrium'.

Related to variations in velocity and direction is sediment supply. Sediment supply may fluctuate in areas where wind direction is variable. These periodic increases and decreases to the erosion/deposition balance will disrupt the equilibrium of the dune.

To gain an indication of 'equilibrium', the ratio of erosion to deposition was determined for both Line One and Line Two in both experiments (Tables 7.1 and 7.2). This was achieved by calculating the total amount of either erosion and/or deposition for all six runs, giving both a 'positive' (deposition) and a 'negative' (erosion) total. A result of 1.0 indicates equality of erosion and deposition; the extent of the deviation from this result gives an indication of how more or less erosion is occurring than deposition.

It is apparent from the data presented in Tables 7.1 and 7.2 that over shorter measuring periods (one day), the e/d ratio appears inaccurate. This is particularly true for Experiment Two. However, what is noticeable is the trend that develops over a few days. Over the entire experimental period, the e/d ratio decreases. For Line One (both experiments) this

**Sand Transport #**  
**Line One**

Date	Erosion (total)	Dep'n (total)	Erosion (e) (%)	Dep'n (d) (%)	Ratio (e/d)
27/8	547	779	41	62	0.70
27/8 - 29/8	662	1065	38	64	0.61
27/8 - 30/8	732	1261	36	36	0.56

**Line Two**

27/8	231	888	21	79	0.27
27/8 - 29/8	334	1291	21	79	0.27
27/8 - 30/8	378	1674	18	82	0.22

**Spatial Variation \***

**Line One**

**Line Two**

Date	Deposition	Erosion	Deposition	Erosion
27/8	54	29	38	48
27/8 - 29/8	45	55	43	57
27/8 - 30/8	45	36	43	57

\* some amounts do not equal 100; this is attributable to sediment movement through the transportational zone, which is not part of the erosion/deposition ratio.

# data obtained from erosion pin measurements

**Table 7.1 Sand transport data - Experiment One,  
Line One and Two**

**Sand Transport <sup>#</sup>**  
**Line One**

Date	Erosion (total)	Dep'n (total)	Erosion (e) (%)	Dep'n (d) (%)	Ratio (e/d)
4/10	31	11	74	26	2.8
4/10 - 7/10	246	332	43	57	0.74
4/10 - 9/10	525	871	38	62	0.56

**Line Two**

4/10	17	11	61	39	6.0
4/10 - 7/10	126	528	19	81	0.24
4/10 - 9/10	459	1130	28	72	0.38

**Spatial Variation <sup>\*</sup>**

**Line One**

**Line Two**

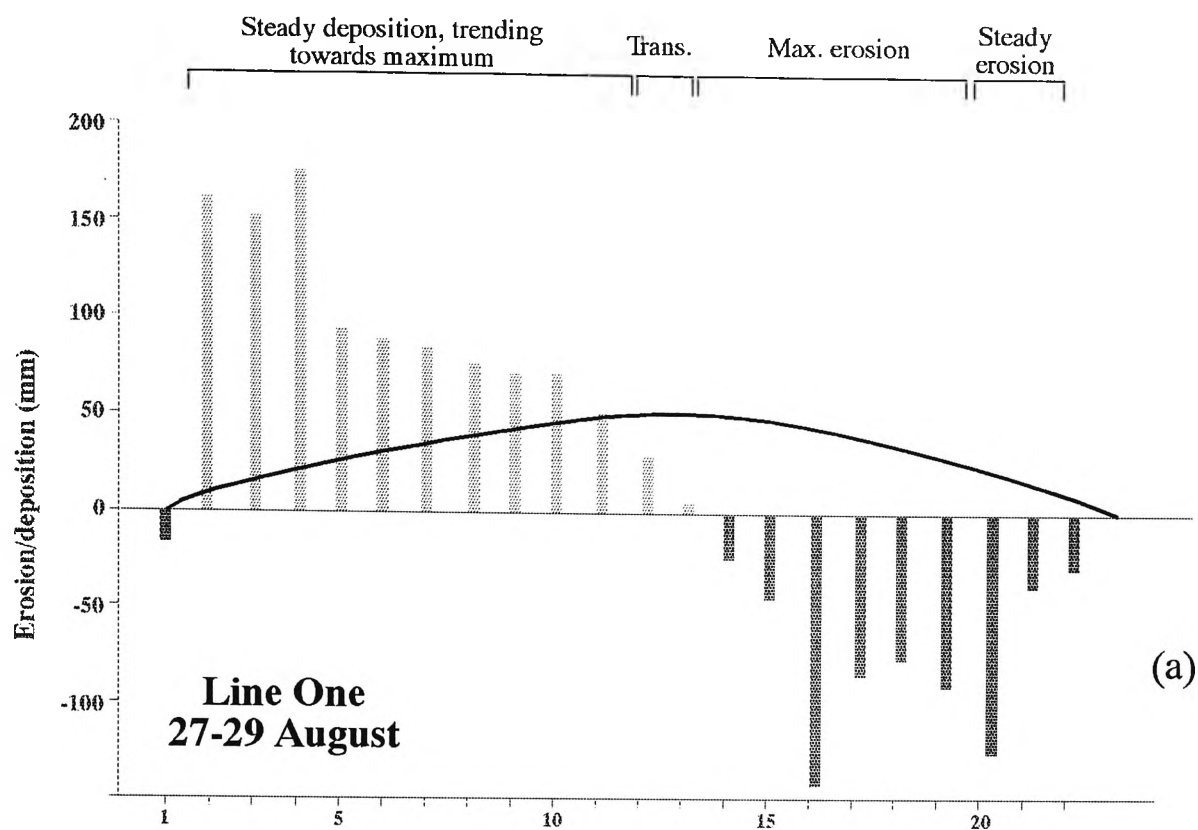
Date	Deposition	Erosion	Deposition	Erosion
4/10	(no pattern evident)		10	90
4/10 - 7/10	41	59	20	80
4/10 - 9/10	36	64	20	80

\* some amounts do not equal 100; this is attributable to sediment movement through the transportational zone, which is not part of the erosion/deposition ratio.

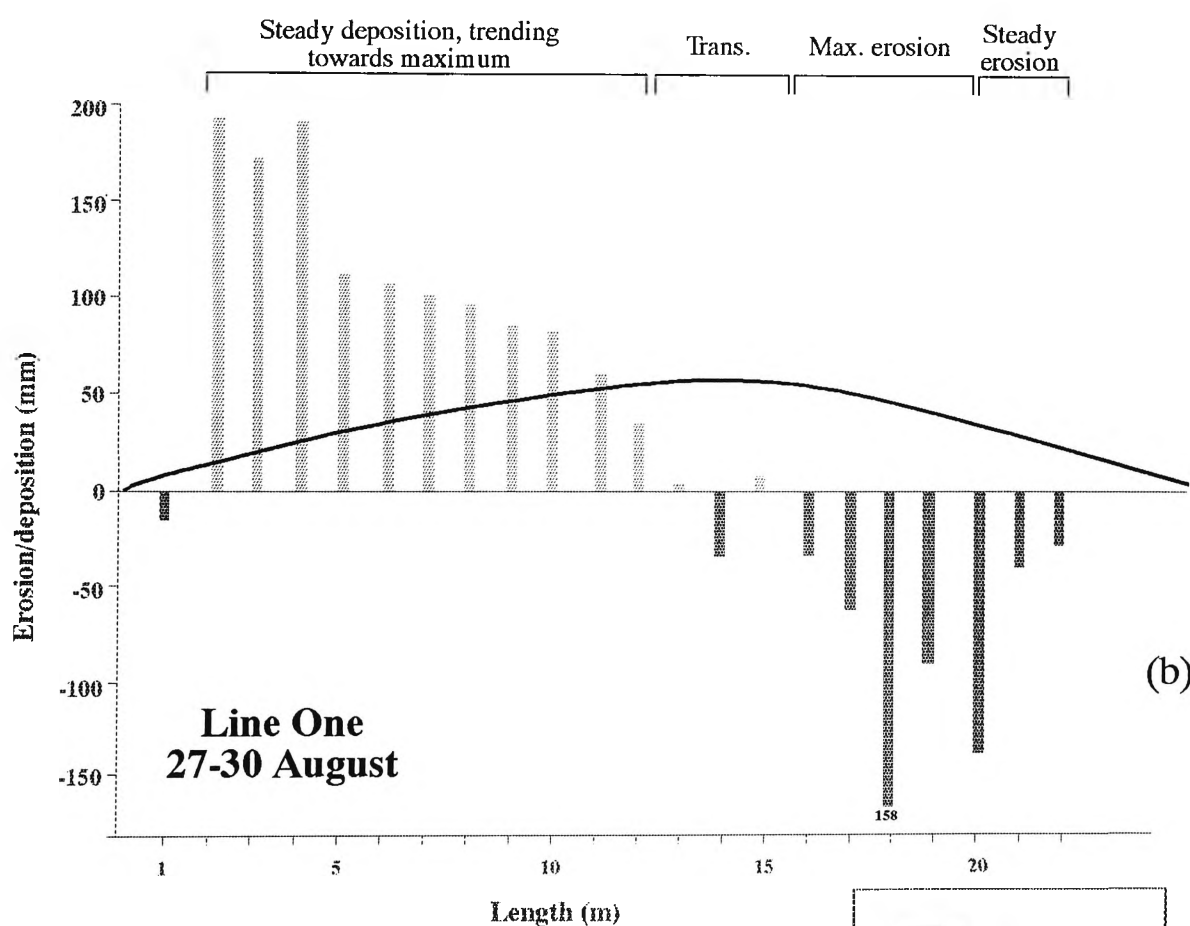
# data obtained from erosion pin measurements

**Table 7.2 Sand transport data - Experiment Two,  
Line One and Two**



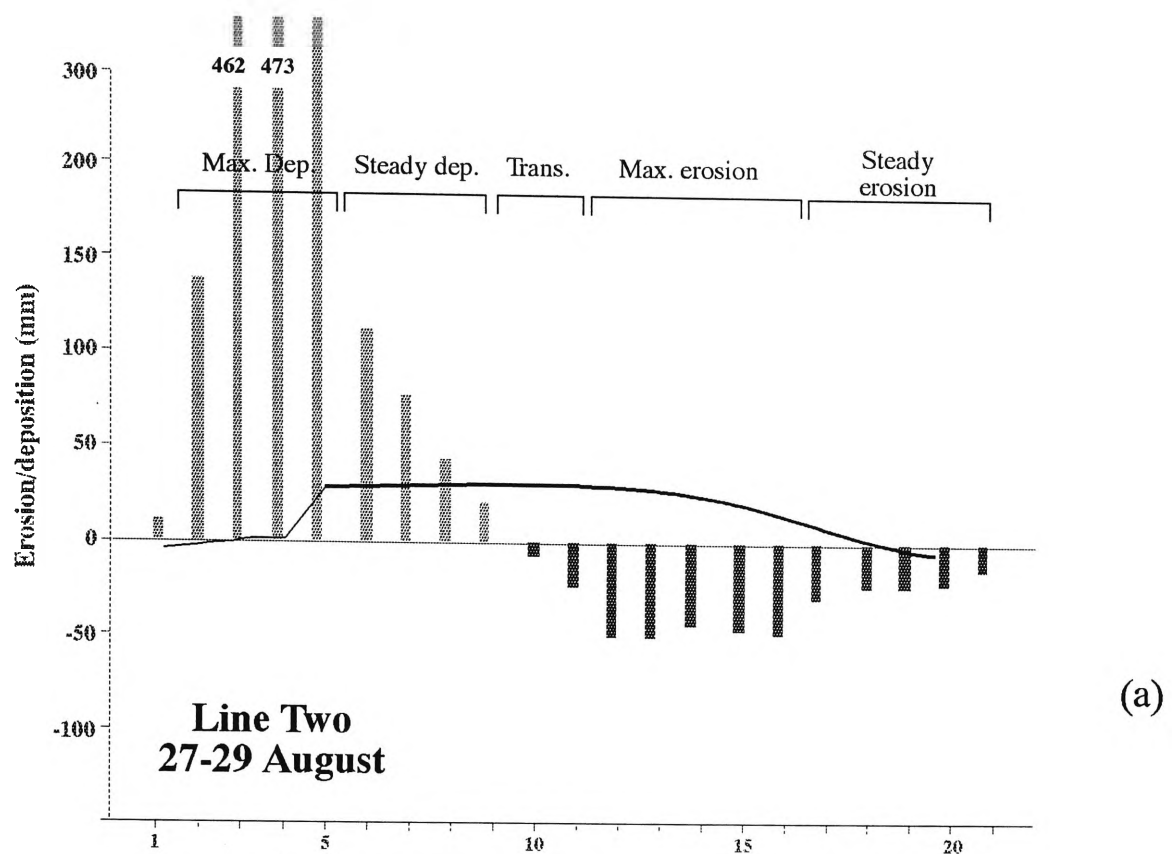


(a)

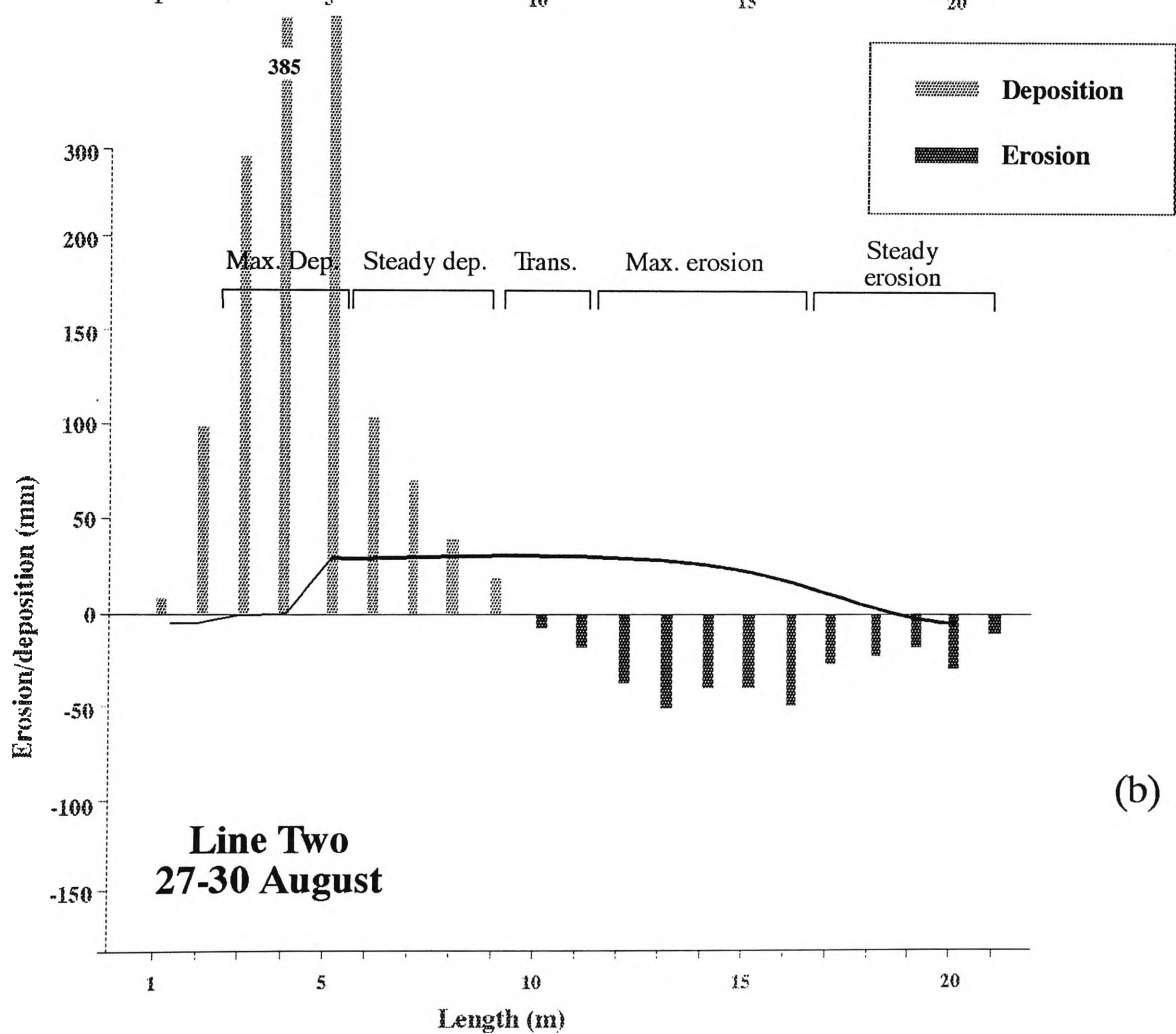


(b)

**Figure 7.18a Sand transport patterns (Experiment One) showing spatial distribution of erosion/deposition**



(a)



(b)

**Figure 7.18b Sand transport patterns (Experiment One) showing spatial distribution of erosion/deposition**

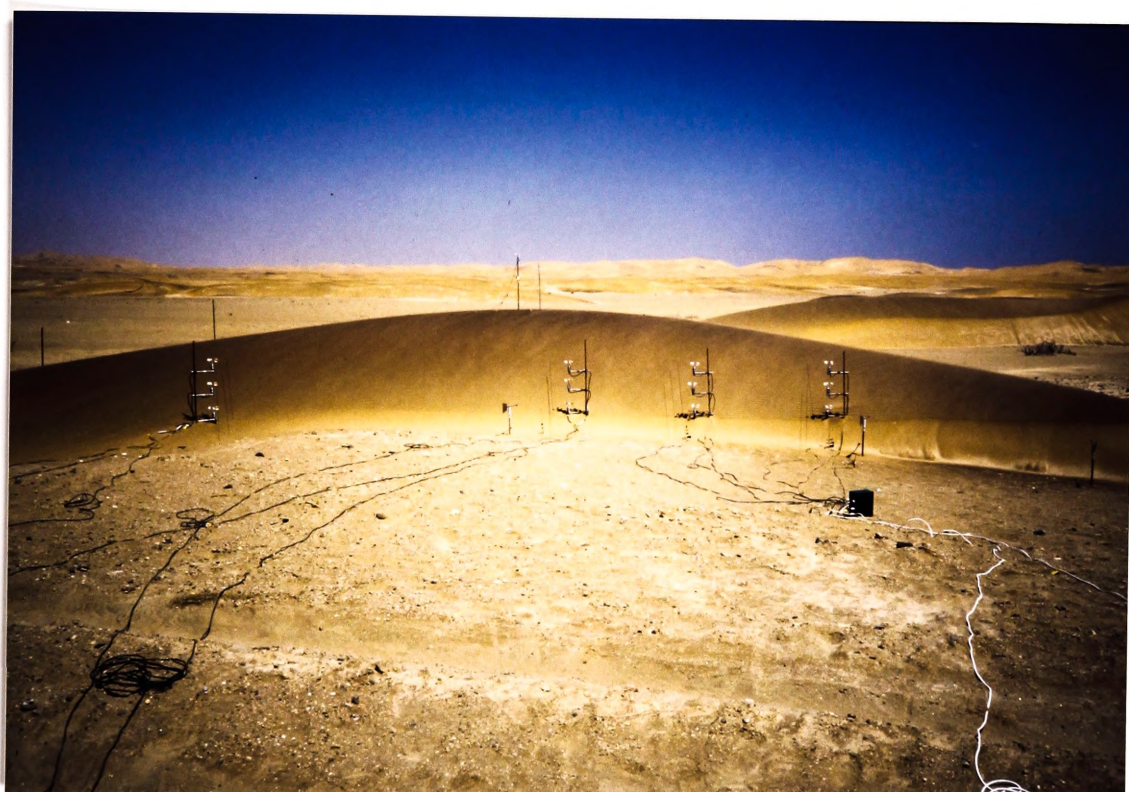
decrease indicates a corresponding trend away from equilibrium, as deposition increases. The ratios for Line Two (Experiment One) also decrease, indicating that deposition is continuing to increase over the lee slope. An example illustrating the spatial distribution of erosion and deposition is shown in Figure 7.18a and 7.18b.

It is an interesting situation, where one part of the dune, only six metres from the other part, has such a different morphology and corresponding flow characteristics. These experiments have demonstrated that flow velocity is a significant factor in erosion/deposition patterns, and that a dome represents a more 'equilibrium' form than a barchan, *based solely on sand transport and velocity profiles*. Subsequent experiments will attempt to measure not only these characteristics, but also to further determine the role of flow velocity on the development of a slipface.

## 7.5 EXPERIMENT 3 (9 October 1989) (Swakopmund 3)

### 7.5.1 Velocity Profiles


Further flow experiments were conducted on SW3 on 9 October. Similar to SW1, SW3 had a fully developed slipface on one side and no slipface on the other (Photograph 7.3). As with previous experiments, the aim was to compare flow characteristics and sand transport across both of these profiles. However, this experiment concentrated on the lee slope area only. For this experiment four masts were placed across the front (or northeastern edge) of the dune crest (Figures 7.19a and 7.19b). Each mast contained three anemometers at heights of 550, 250, and 120 mm. A permanent mast was positioned at the highest point on the dune at a height of 900 mm. Velocity readings commenced at 12:58 and continued until 14:14 at 2-minute intervals. A total of 9 runs were recorded. Unfortunately, Mast Four anemometers did not function correctly and are not discussed further.



**Photograph 7.3 Anemometer array, Experiment Three**

Masts, with anemometers,  
with heights as shown.  
(Masts numbers are noted  
above each mast).

550 mm  
250 mm  
120 mm

 = slipface

Note: the mast positions and anemometer  
heights are approximate

Permanent  
Mast  
(900mm)

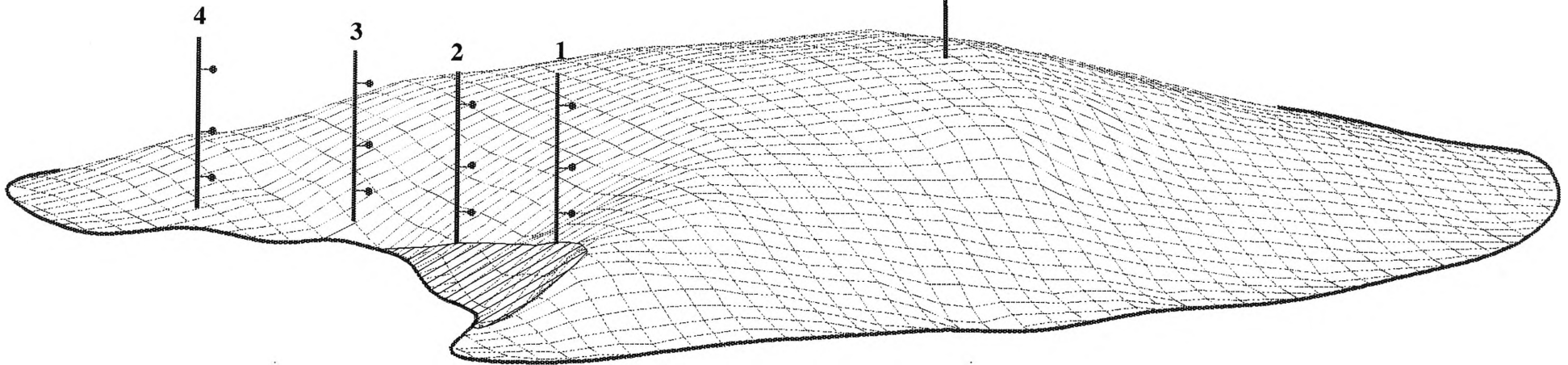
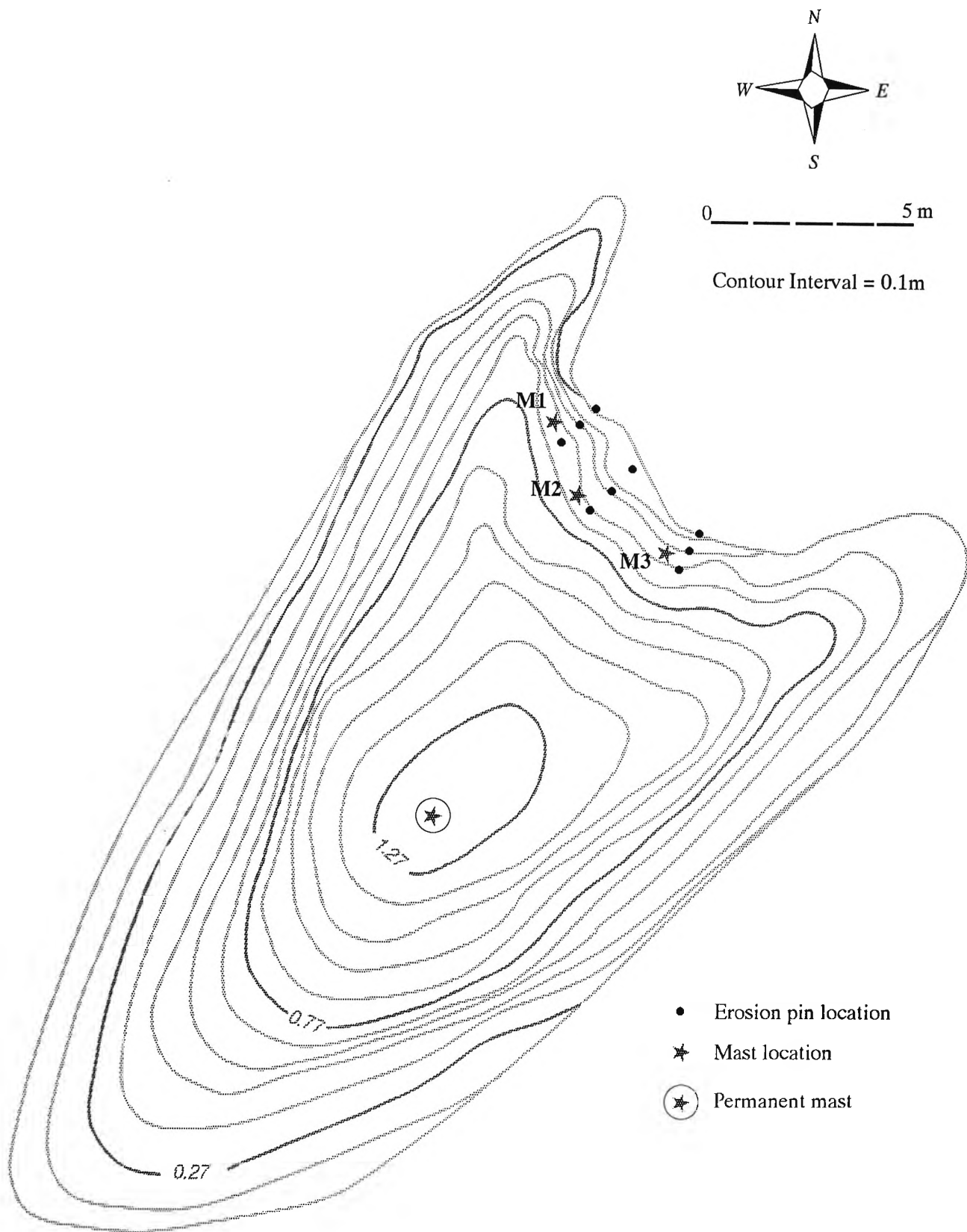


Figure 7.19a Location of masts, Experiment Three



**Figure 7.19b Location of erosion pins and masts,  
Experiment Three**

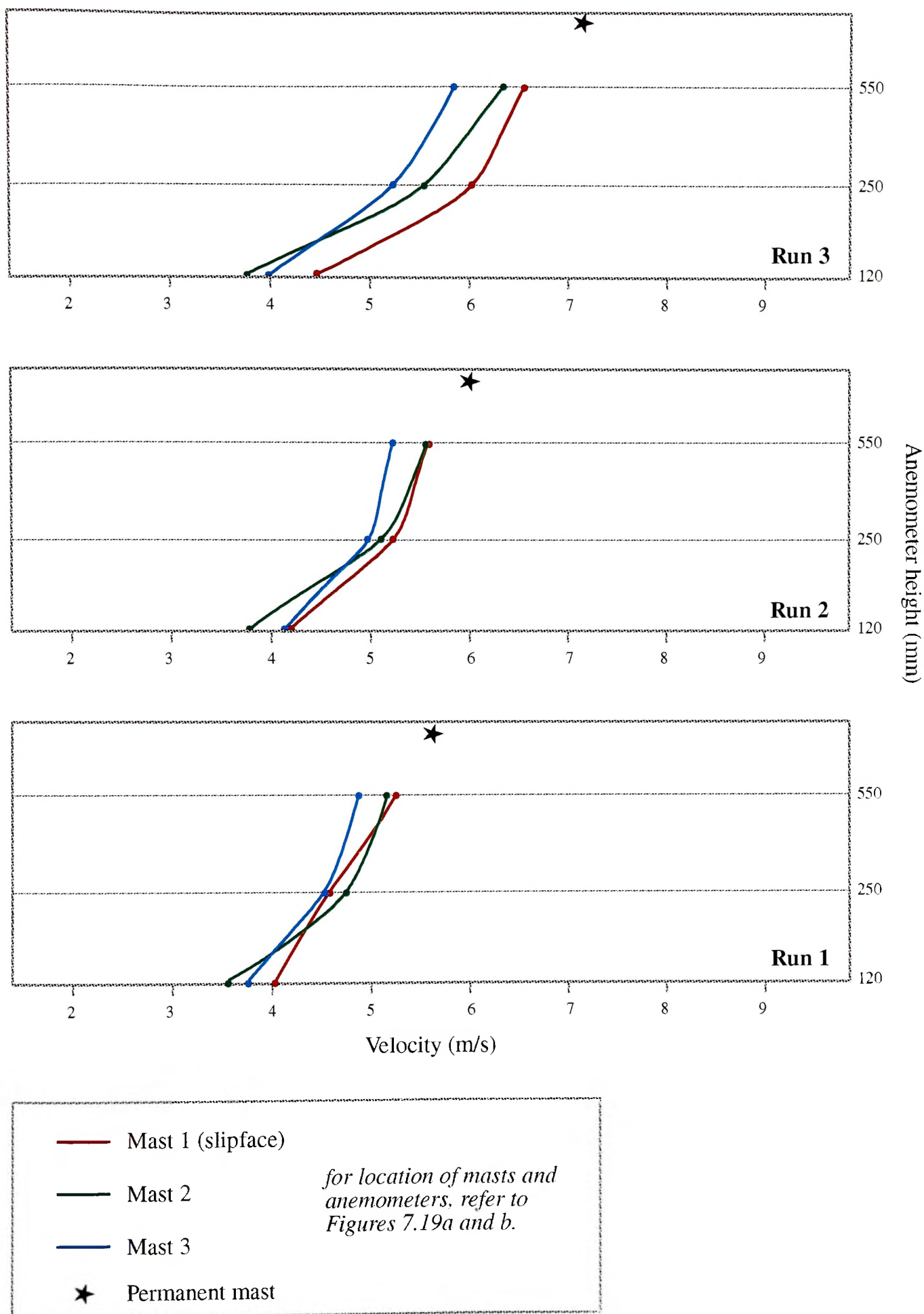
Three erosion pins were placed alongside each mast, starting at the base of the dune and continuing to the crest, or top of the slipface. Six erosion pin readings were taken every 30 minutes until 15:15.

Velocity readings commenced at 12:58 and ended at 14:14. The average reading, taken from the permanent mast (.9m) was 7.11 m/sec. The lowest reading was 5.16 m/sec recorded at the onset of the experiment. Velocities gradually increased over the experimental period, with the highest velocity (7.76 m/sec) recorded at 14:12.

Velocity profiles for Experiment 3 (Fig. 7.20) indicate the highest velocities occur on the Mast One anemometers, located at the top of the slipface. Mast Two velocity readings are nearly as high as Mast One readings and for some runs the measurements are almost equal. The velocity readings for Mast Three, located on the non-slipfaced portion of the dune, are the lowest.

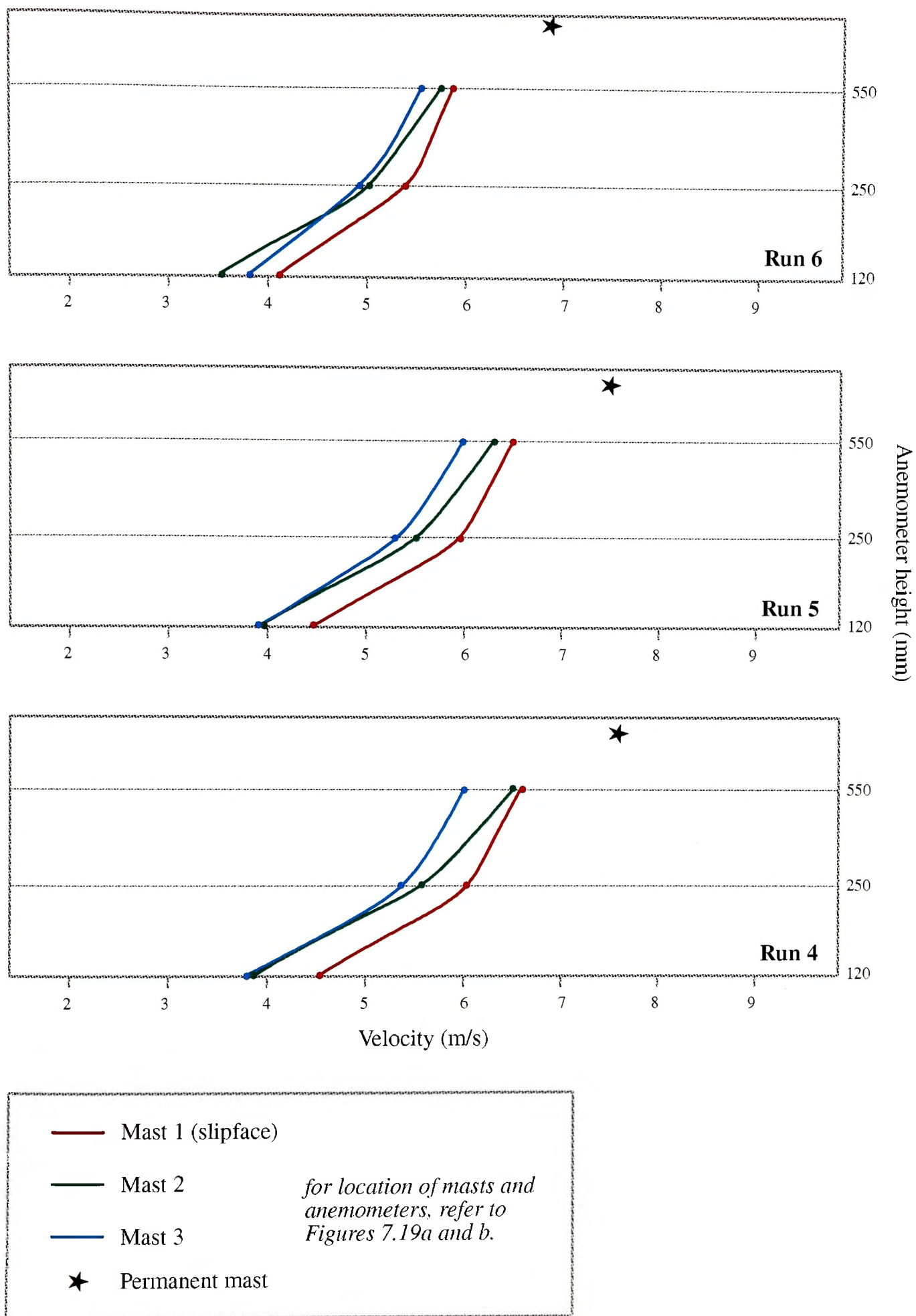
It is expected that the highest velocities would occur at the top of the slipface (Mast One), and gradually decrease as the slope decreases, towards Mast Three. As discussed above, Mast One velocities are consistently higher than the other measured velocities, except when permanent mast readings are comparatively lower. At these lower velocities (<7 m/sec), Masts One and Two exhibit very similar velocities at the 550mm level. These flow patterns are consistent with the results for both low slopes and slipfaces obtained from the previous experiments. A comparison of the velocity profiles for Mast One (Line Two) and Mast Two (Line One) (Experiment One), located in approximately the same positions as Masts One and Two of Experiment Three, indicate that at the 500mm level, the flow structure is similar, with the anemometer at the top of the slipface registering higher velocities than the one located at a similar position over a low slope. However, as velocities increase, flow over the low slope becomes increasingly concave, as discussed in section 7.2.3. This flow structure is also





**Figure 7.20 Velocity profiles, Experiment Three**





**Figure 7.20 (con't) Velocity profiles, Experiment Three**

apparent in the results for Experiment Two, when Mast Two (Line Two) and Mast Four (Line One) are compared. Sand transport patterns reflect these velocity and slope variations, and will be discussed in the following section.

### 7.5.2 Sand Transport

Three erosion pins per mast were used to measure sand transport. A line of pins began at the crest of the dune and extended to just beyond the base. Measurements were taken at approximately 30 minute intervals from 13:20 to 15:15 for a total of five readings per pin (Fig. 7.21).

Sand transport on the slipface is dominated by deposition. Maximum deposition occurs at the crest of the dune, decreasing towards the base. At Mast Two, where a partial slipface is present, the patterns are similar at the crest of the dune. For both lines of pins, deposition patterns correspond well with wind velocity readings. As crest velocity increases, the rate of sand deposition also increases. Deposition occurs across the Mast Three pins, although the actual amount is significantly less. Measurements at Pin 3 indicate slight deposition occurred over the measurement period, with three measurements recording no change.

Since few pins were used over a short distance in this experiment, it is not possible to determine erosion and depositional zones over the entire length of the dune, as in the previous experiments. However, the measurements show that deposition for Mast One through Mast Three pins was concentrated near the crest of the dune, with Mast One and Two having the highest amount of deposition (Fig. 7.22a-c). Over the measuring period, the dune advanced approximately 70mm at Mast One and Mast Two. At Mast Three, very little movement occurred. Due to survey error, no measurements were made at Mast Four. From these results it is apparent that deposition is concentrated near the slipface crest over short

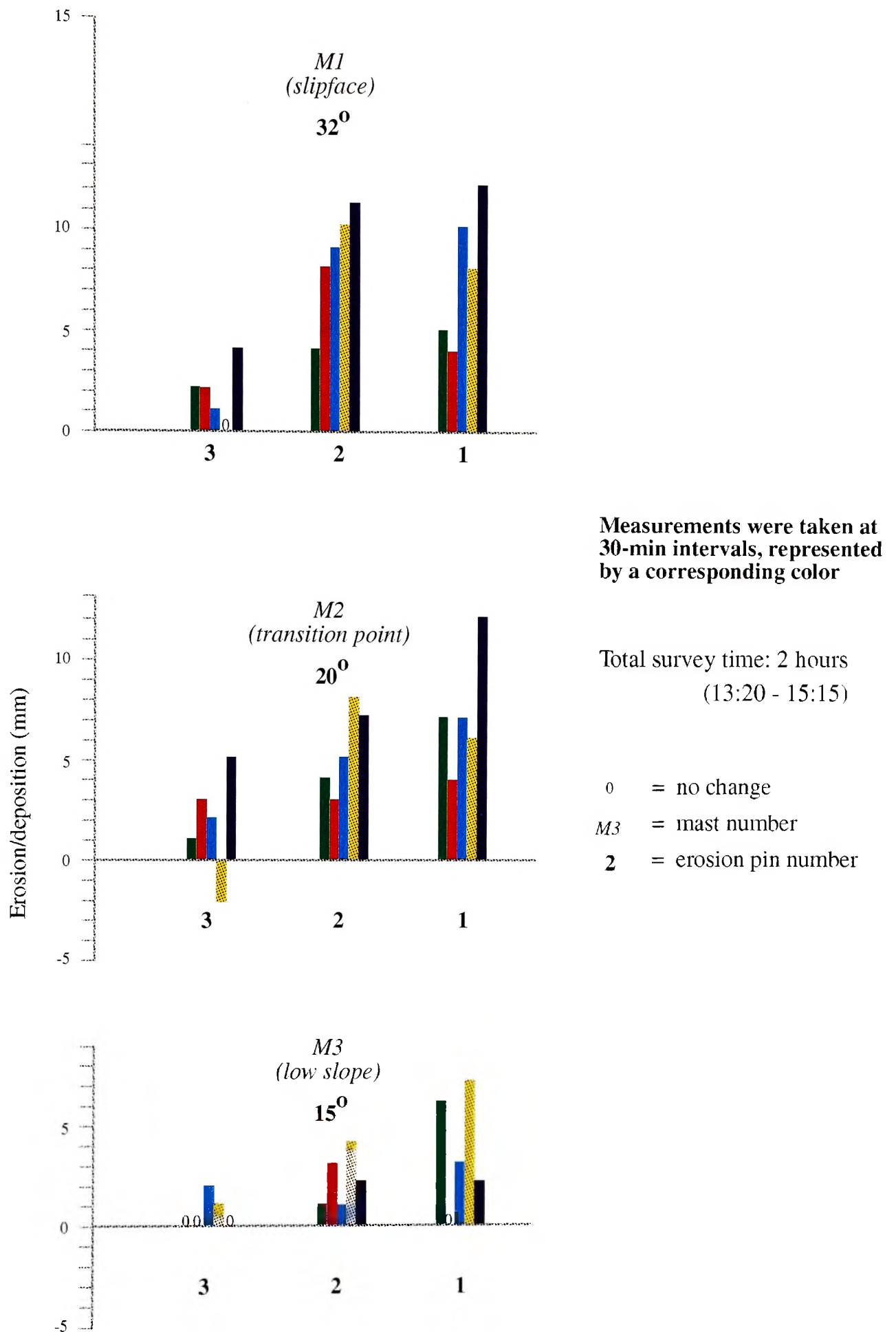
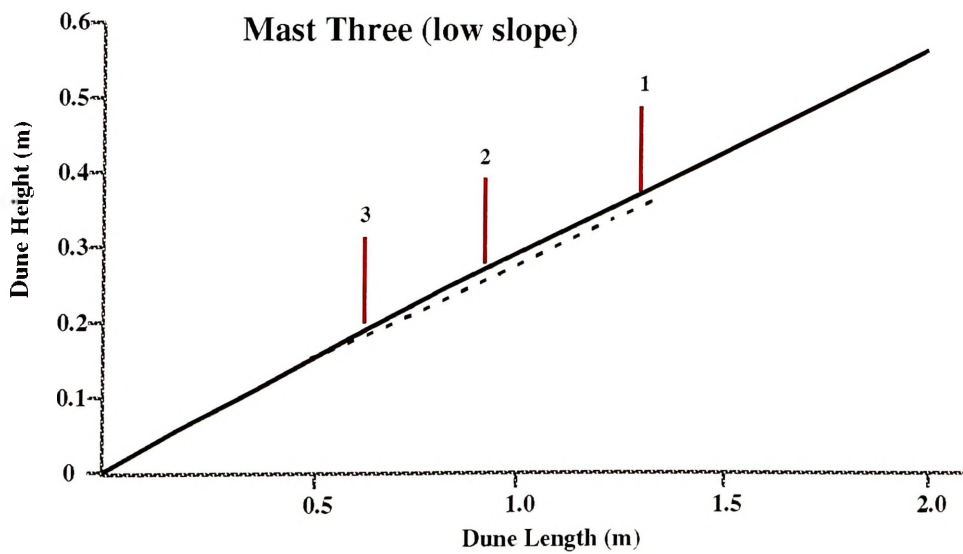
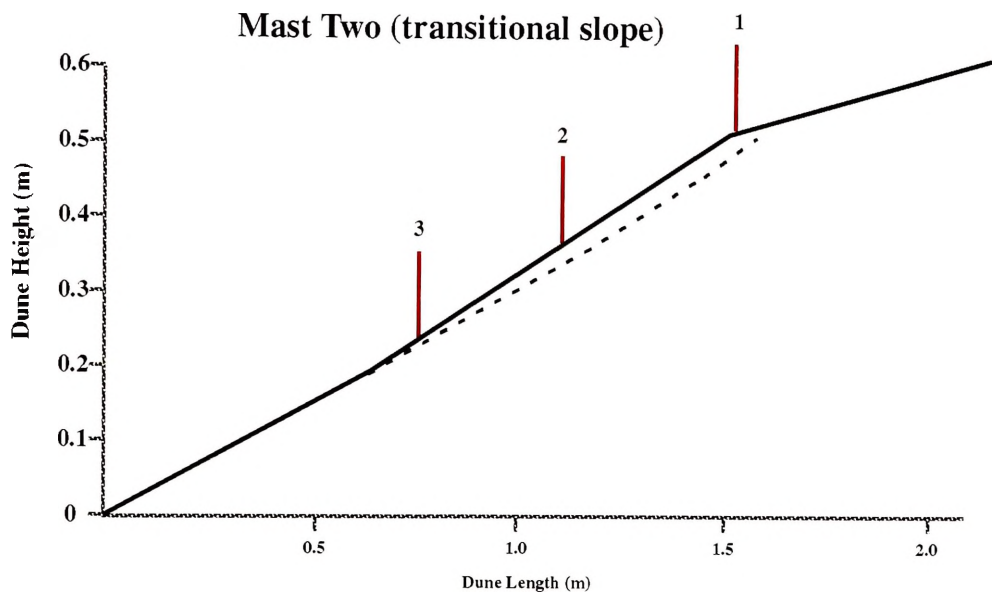
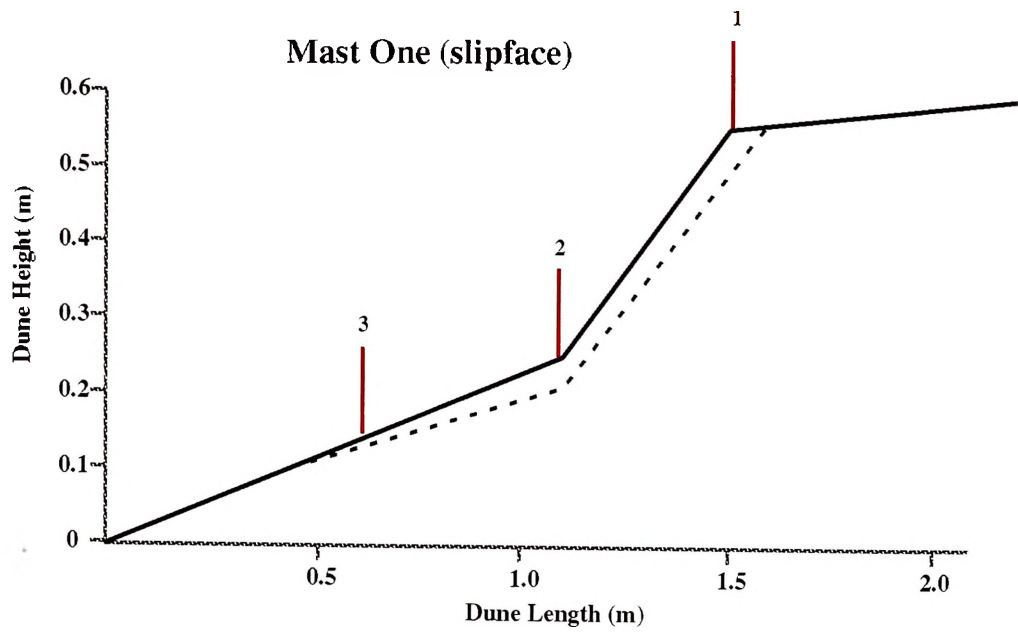


Figure 7.21 Sand transport, Experiment Three



**Figure 7.22 Erosion and deposition over three slopes, Experiment Three**

periods as observed by others (Hunter, 1985). Periodic slumping occurs as the slope adjusts to the increased deposition.

The experimental period was comparatively short (~ 2.5 hours), and during this time, wind velocities varied little, remaining between 5.5 and 7.5 m/sec. Deposition increases over the measurement period, although corresponding velocity measurements do not vary greatly. No velocity data were available for the last two erosion pin measurements, where deposition increases markedly near Masts One and Two. It can only be assumed from this data that velocity had increased over this time, as would not be unexpected, given the common occurrence of increasing afternoon seabreezes in the area.

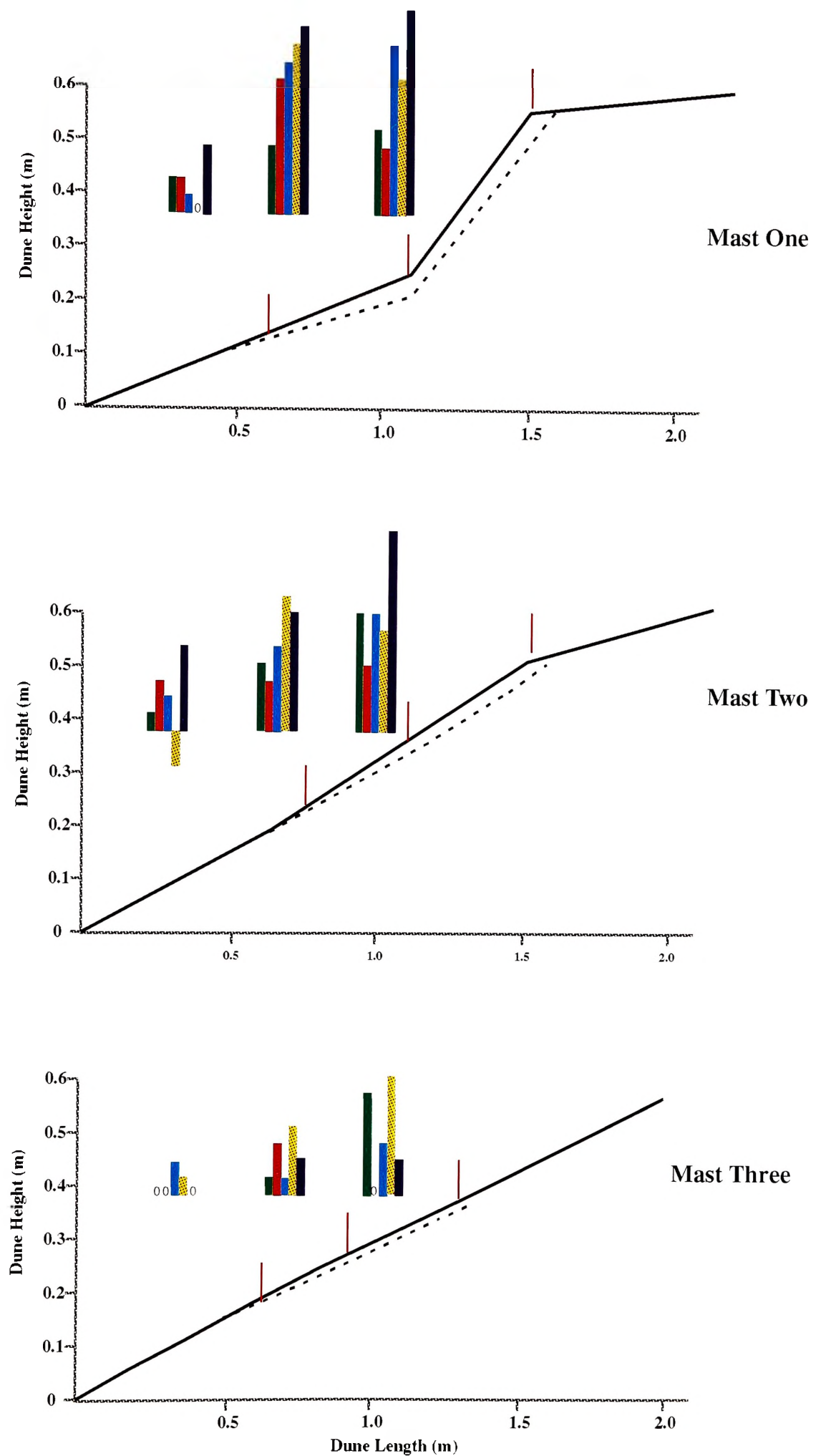
### 7.5.3 Summary (Experiment 3)

The topographic surveys show a regular increase in slope angle between Masts Three, Two, and One, with a  $17^\circ$  difference in slope angle between Mast One and Mast Three (Fig. 7.22). The Mast Three slope was measured at  $15^\circ$ . This slope angle increases to  $20^\circ$  at Mast Two and  $32^\circ$  at Mast One. Masts One and Three indicate the two extremes of lee slope deposition, with Mast Two occupying an intermediate position between the two. This experiment, unlike the previous experiments, has shown the degree of slope development which occurs between these two slopes. The primary difference between the Mast One slope (slipface) and the Mast Three slope is the increasing degree of deposition which occurs over a decreasing area. At Mast Three, deposition is minimal and decreases with distance downwind approaching zero near the base of the slope (Fig. 7.22). At Mast Two, this pattern is also apparent, but the amount of deposition has increased at the top of the slope. At Mast One, deposition is at a maximum just on the slipface.

The increasing deposition occurring from Mast Three to Mast One indicates that the dune is assuming a more asymmetrical profile. Sediment is deposited across the dune in an increasingly shorter space (i.e. over less distance) as the slope increases. The Mast Two slope (Fig 7.23) shows that deposition is increasingly located towards the upper slope face. This may occur perhaps because limited flow separation occurs at, or below this dune angle ( $\leq 20^\circ$ ). If this deposition pattern continues even as the dune migrates forwards, the lee face must increase in slope angle. This probably accounts for the break in slope at 15m on Figure 7.23. Continued maximum deposition near the top of the slope would eventually lead to an increasing slope angle, increased flow reversal and separation and the development of a slipface as is shown at Mast One. This increasing slope asymmetry occurs as part of the evolutionary process from dome to barchan, and appears to be a pre-requisite for slipface development, as discussed in Chapter Six.

Comparison of the upwind topographic profiles (Fig. 7.19a) shows that the upwind slope leading to Mast One is shorter and steeper than that leading to Mast Two. Each mast, from One to Three has an increasingly longer upwind slope. This explains why the crest velocity at Mast One is slightly higher than the others since flow compression would be greater over the shorter, steeper Mast One slope. Additionally, Mast One is located at the dune crest just upwind of the edge of the slipface, while Masts Two and Three are located on leeward (convex downwind) slopes. The results from the previous experiments demonstrate that these positions would naturally display lower velocities than those found at the crest of the dune above the slipface.

There are significant differences in the volume of sand deposited at Mast Three ( $15^\circ$  slope) compared to Masts Two ( $20^\circ$ ) and One ( $32^\circ$ ). Sand transport would tend to be greater at Mast One because, as explained above, the speedup on this part of the dune should be greater, hence the greater depositional rate and magnitude. As flow separation increases, grain



**Figure 7.23 Erosion and deposition over three slopes, Experiment Three**

deposition would be increasingly affected and a larger amount of sand would fall within the separation zone around Mast One, compared to Masts Two and Three. The differences in sand deposition volume may also be attributable to (i) sediment deposition further up the mast 3 windward slope, outside the Mast 3 measurement area, resulting in deposition at the dune crest. Such a pattern of deposition is observable in previous experiments; (ii) a lesser volume of sand added to the dune, or eroded off the dune (the latter feasible since this is the longest, lowest slope and should therefore have the least relative transport); and (iii) loss of sediment off the dune downwind.

From these results and the results of the previous experiments, it may be concluded that the critical slope angle for flow separation to occur must be around  $20^\circ$  or so ( $\pm 2-3^\circ$ ), and that this increasing slope angle occurs as part of the evolutionary process from a smooth low-angle slope to a slipface.

## 7.6 CONCLUSION

Results for Experiment Two were similar to those for Experiment One. In fact, the primary difference between the experiments was that Experiment Two included flow measurements over the windward slope. Experiment One, however, provided a range of velocities, allowing comparisons to be made between these varying velocities and sand transport across Line One (domed) and Line Two (slipface). Experiment Three concentrated on the lee slope itself, over a trend from low slope to slipface. The results were consistent with the previous experiments. The following conclusions may be drawn, based on the results of these experiments:

(1) Deposition is significantly higher and more contained over a lee slope containing a slipface than it is over a non-slipfaced slope. This deposition increases as velocity increases.



Deposition is concentrated at the top of the slipface, and may result in an increase in dune height. This is not apparent over a non-slipfaced slope, where height does not tend to increase, despite significant deposition. This massive amount of deposition must eventually result in avalanching (Photograph 7.1), as failure due to overloading by grainfall reduces the slipface from the angle of initial yield to the angle of repose, or the residual angle after shearing (Hunter, 1985). Hoyt (1966) observed that rapid deposition near the dune crest results in periodic slumps and slides down the lee slope.

Velocity profiles indicate flow separation and reversal is evident over these slipfaces, following speed-up over the windward slope. This speed-up increases sediment transport through the transportation zone (see below), but over a slipface the velocity is not maintained, due to a sudden decrease in pressure, resulting in a high rate of deposition. Flow separation was not observed over the non-slipfaced slopes; consequently, deposition rates were far less, and very closely equalled erosion rates.

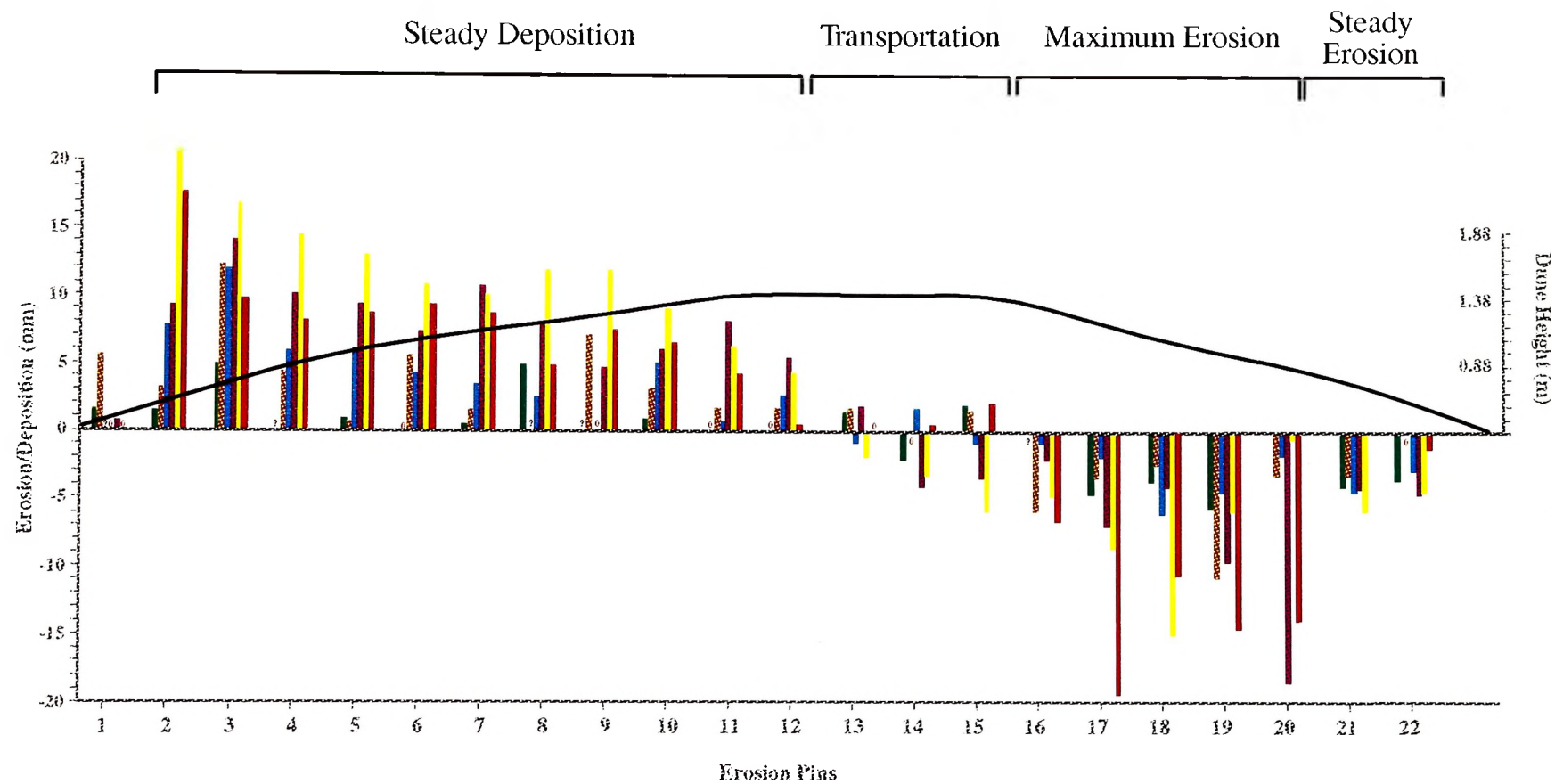
(2) From the collected data, and information from previous studies of flow separation and sediment transport, two primary controls on the development of a slipface are recognized, both of which either act separately, or in conjunction, all other variables (grain size, dune height, roughness) being equal. One of these primary controls is wind velocity; a secondary, but by no means less important control is wind direction. The second primary control is windward slope length; a secondary control associated with slope length is slope angle; in many cases a longer windward slope will also exhibit a lower slope angle, and vice versa.

The decreased length of the windward slope adjacent to the slipfaced lee slope allows flow to attain a higher velocity over the dune crest, due to the shorter distance and greater rates of flow compression, thereby increasing sediment transport over this shorter area. As

previously discussed, the sudden decrease in pressure at the top of the lee slope results in massive deposition of this entrained sediment. Over the longer windward slope, flow velocity is measureably less than that over a windward slope associated with a slipface, as evidenced by the velocity profiles. In addition, the flow structure is more regular, with highest velocities at the crest, which decrease steadily down the lee slope. Measured sand transport is in equilibrium (or nearly so) with the flow over this slope, with eroded sediment transported and deposited near the top of the lee slope.

(3) From the sand transport data collected for these experiments, it is possible to define a series of transport zones over both a slipfaced slope and a slope without a slipface. These zones are based on those identified by Petrov (1976) outlined in Chapter One.

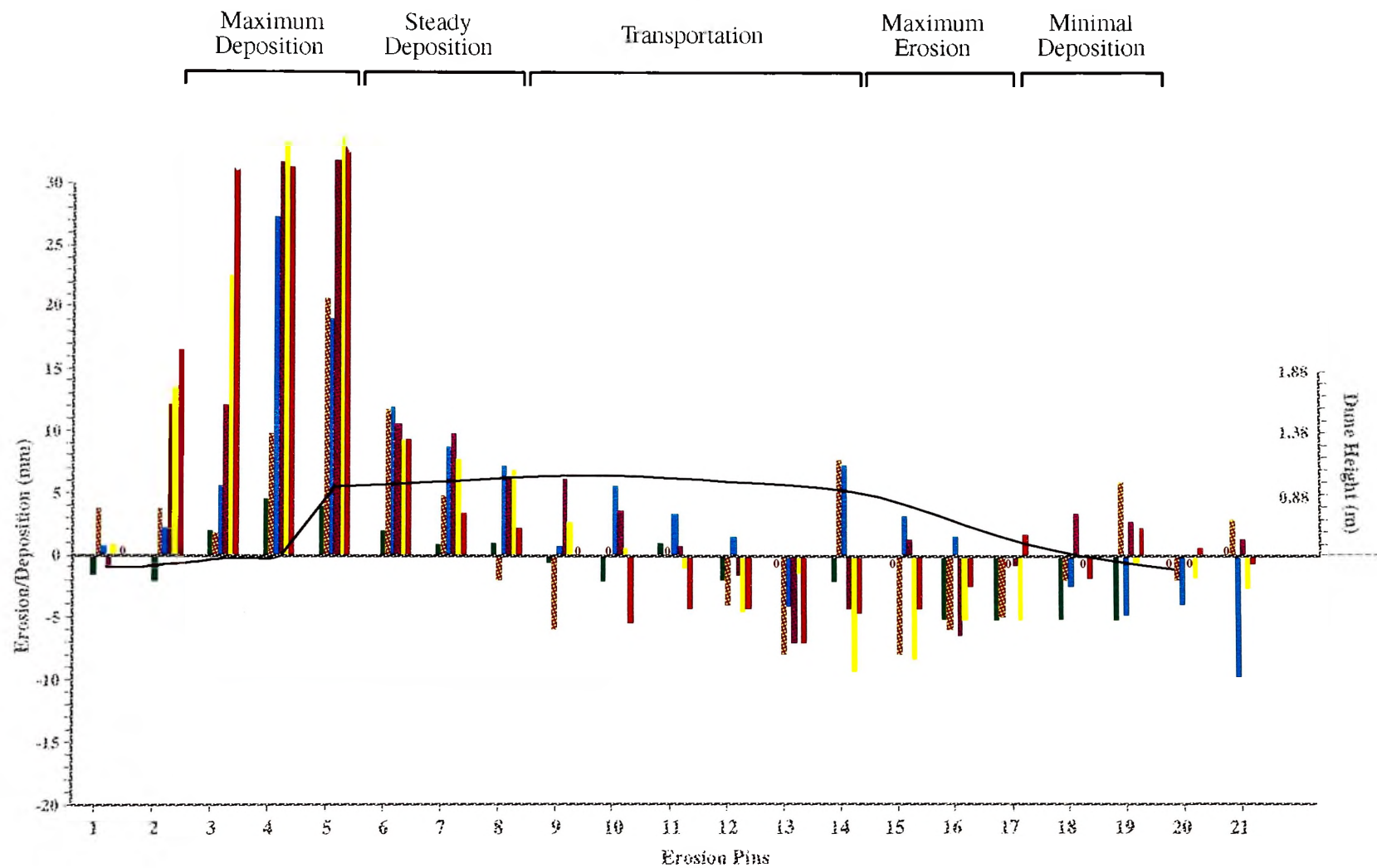
The results from Experiments One and Two allow further subdivisions of Petrov's zones (Figure 7.24). Slight variations in zone delineation occurs over a slipface and non-slipfaced slopes. Over a slipface, a zone of maximum deposition may be identified, which is not present over a non-slipfaced slope. Immediately upwind of the maximum deposition zone, there is an area of steady deposition, noticeable in both types of slopes. A zone of transportation is found at the highest point of each slope type. Here, the process of deposition changes to one of erosion. This zone, quite small in area, is characterized by a marked decrease in deposition as a transition occurs from this process to one of erosion. Continuing upwind, the next zone is one of maximum erosion, which occurs over a significant portion of the windward slope. Slopes with a slipface exhibit less erosion here than those without a slipface, a pattern consistent with the idea of equilibrium forms. The final recognizable zone is one where steady erosion occurs. Here it is also possible to have a small area of deposition at the toe of the windward slope as velocity drops slightly. This deposition appears to occur more often over slipfaced lee slopes than those without a slipface.



Time	Velocity (m/sec) (Perm. Mast)	
14:30	7.8	
15:05	8.8	
15:40	---	? = questionable data
16:25	-10	0 = no change
17:28	10.8	
18:23	9.5	

Line One

Figure 7.24 Sand transport zones over a non-slipfaced slope



Time	Velocity (m/sec) (Perm. Mast)	
14:30	7.8	
15:05	8.8	
15:40	---	
16:25	10	
17:28	10.8	
18:23	9.5	

0 = no change

Line Two

Figure 7.24 (con't) Sand transport over a slipface

Howard and Walmsley (1985) recognized that patterns of erosion and deposition over a model dune are sensitive to minor variations in the shape of the (windward) slope and roughness height. From the experimental data presented in section (2), it appears that windward slope length must be considered when discussing slipface development. Length is a determining factor of slope shape; a longer slope means a longer dune and therefore one with a different shape than a dune with a shorter windward slope length, at a constant height.

In addition to the sensitivity to slope shape, the zones of erosion and deposition over a dune are also time-dependent, i.e. they are distinct only after a reasonable length of time has elapsed, especially at low wind speeds. However, time may become a less significant factor should wind velocities be sufficiently strong.

The results of Experiment One, where wind velocities were comparatively stronger ( $>7.8$  m/sec) over the measuring period, the zones are distinct for both slope types, even though the entire measuring period was approximately four hours (Fig. 7.6 and 7.7). Experiment Two results did not strongly indicate the existence of these zones during the 4 October measurement period, which was only 1.5 hours (Fig. 7.16a). However, measurements made on 9 October which included measurements from 4-7 October, provided results which are consistent with these zones (Fig. 7.16c).

To further examine the significance of time vs. velocity in the definition of the transport zones, Experiment One results were made equal to those of Experiment Two. Erosion pin data measuring approximately 2 hours of sand transport was extracted from the existing data set (Fig. 7.25). Wind velocities over this time were between 7.8 and 10.0 m/sec, significantly higher than those measured for Experiment Two. The transport patterns over this shorter time period exhibit similar erosion/deposition characteristics of those derived from a longer measuring period. This result provides an indication that a dune form (both

Time	Velocity (m/sec) (Perm. Mast)	
14:30	7.8	
15:05	8.8	?
15:40	...	= questionable data
16:25	-10	0 = no change

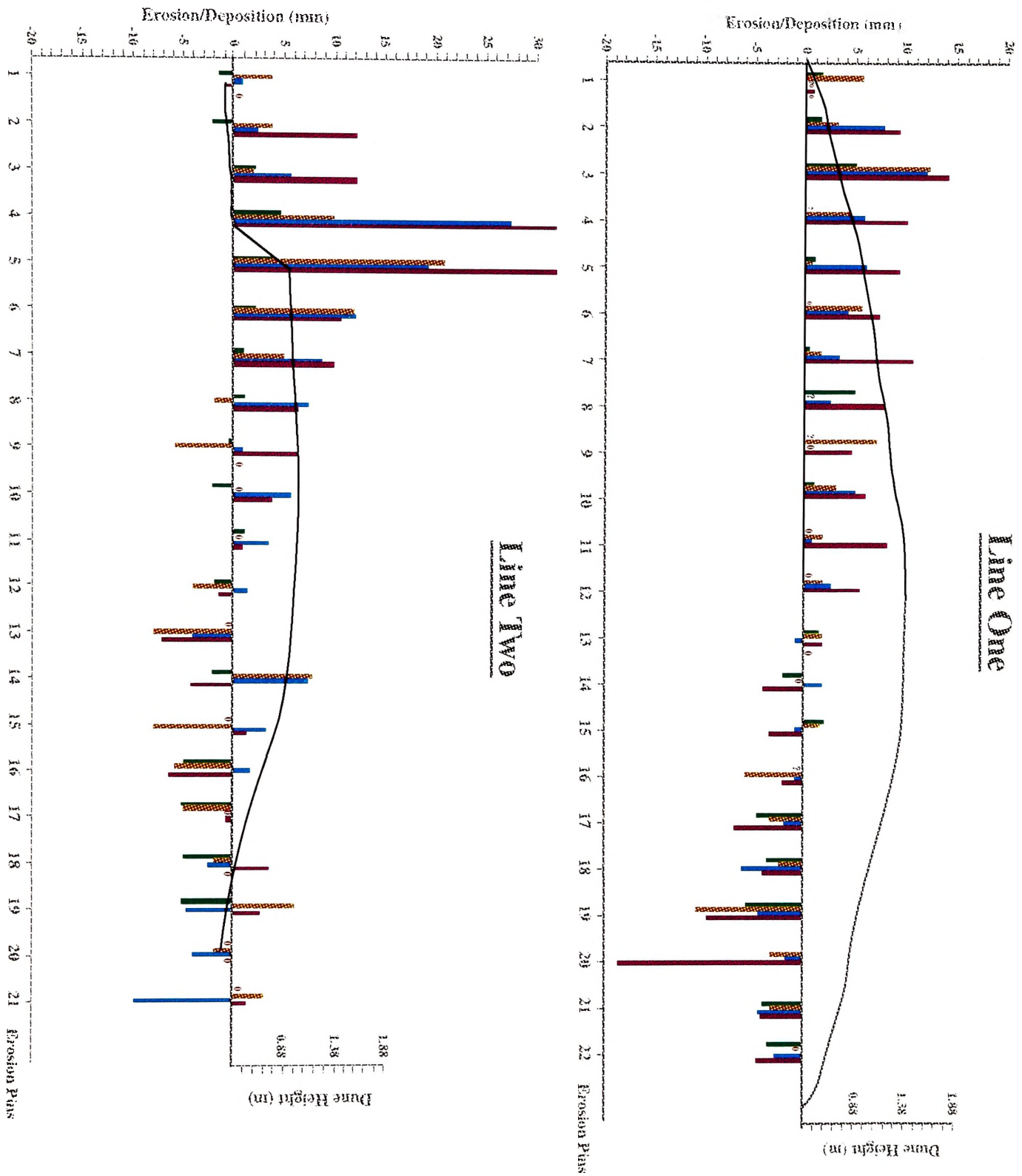


Figure 7.25 Sand transport data, Experiment One (2 hours)

with slipfaced lee slope and without), subject to higher wind velocities, irregardless of time, will exhibit clearly defined zones of erosion, deposition, and transport.

(4) These defined transport zones provide further evidence to substantiate the concept of dune equilibrium, as discussed in section 7.4.1. It is hypothesized that a dome dune, i.e. a dune form with no slipface, represents a form in equilibrium with wind velocity and sand transport. This is not the case with a barchan, where quantified sand transport and velocity profiles indicate a state of disequilibrium. Since a dome represents the first stage of evolution from one dune form to the other, it is possible to observe a pattern of change based on sand transport over time from a non-slipfaced form to one containing a slipface.

Howard (1978) observed that "slight variations in geometry" of the dune relative to the oncoming wind cause major changes in the velocity distribution over the dune, and hence, in the spatial pattern of relative erosion and deposition. It appears from the ratio of erosion to deposition ( $e/d$ ) presented in section 7.4.1 that as the value reaches a certain point, the windward approach slope and the lee slope steepens, and a slipface will develop in response to the increasing sediment deposition, in an attempt to regain an equilibrium form. However, with increasing lee slope development, flow begins to separate, which does not allow the near-slipfaced form to regain its former equilibrium, where flow followed the smooth lower slope contours. Contributors to the initial disequilibrium have been discussed earlier in this section. They are windward slope length and associated angle, which may influence flow and corresponding carrying capacity enough to suppress flow separation over a smooth slope, or increase sediment transport and deposition to the extent that slope adjustment (slipface development) becomes necessary, and the former dome shape is transformed into a barchan or barchanoidal form. Flow divergence around the form account in part for horn development associated with this form, and indeed represent a feedback response to flow/sediment transport changes. Chapter Eight will provide additional discussion on the

characteristics of these and related forms and further observations of their evolutionary relationships.

## 7.7 WIND TUNNEL EXPERIMENTS

A somewhat crude but reasonably effective rectangular wind tunnel, with a working section of 2m x 0.8m, was available for use at the Gobabeb Research Station. At the end of October a series of experiments were undertaken in the wind tunnel in an attempt to observe and record the morphologic changes to an artificially created mound of sand simulating a dome dune under controlled conditions.

### 7.7.1 Run 1

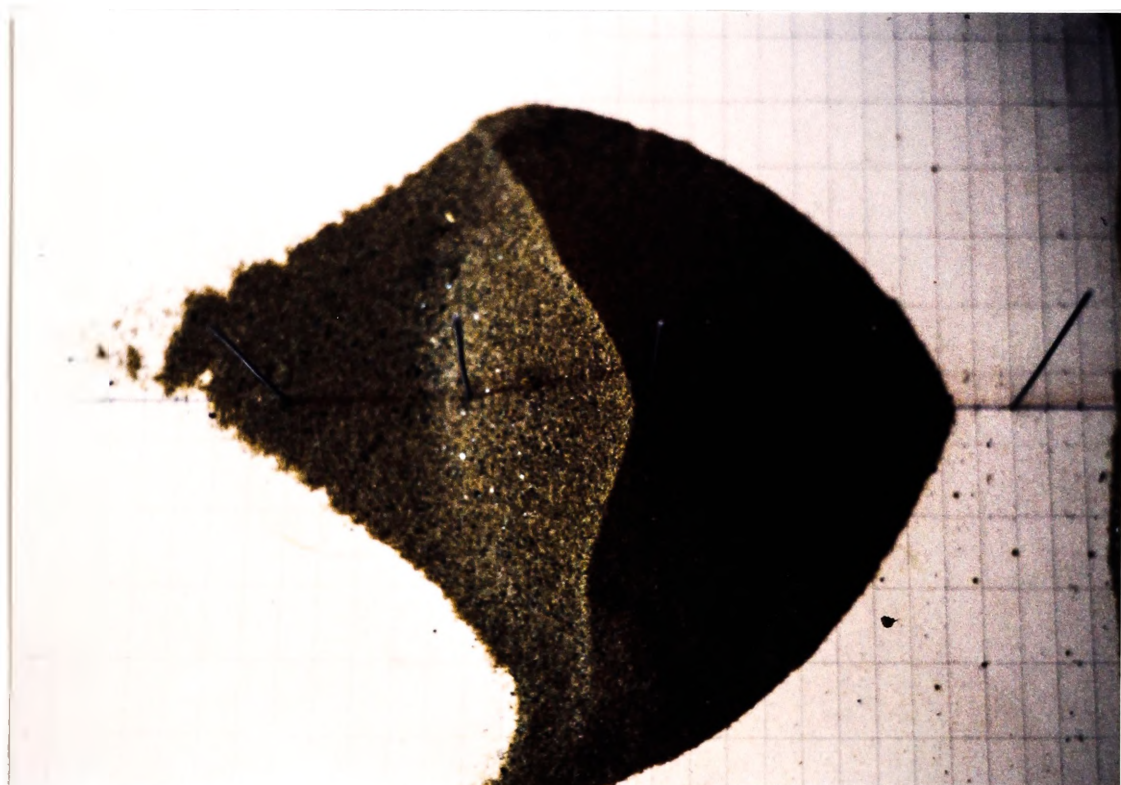
A small 'dome dune' was created with a mixture of sand and river silt and placed inside the tunnel on a piece of thin cardboard upon which a 1cm grid pattern had been drawn. Five small (8cm) erosion pins were placed along the long axis of the model dune. Both the windward and lee slope angles were recorded prior the commencement of the experiment. A plan view of the dune was drawn using the grid as a guide. The model dune was approximately 20 cm in length. A profile was also drawn by placing a ruler at the pins and noting the height of the dune. The model was just over 3 cm in height at the onset of the experiment. The wind flow was applied at 5-minute intervals for a total of 25 minutes. Wind velocity was not measured; maximum tunnel flow velocities were used.

At the end of each of flow sequence, both a plan view a and cross-section profile were drawn for the model dune (Fig. 7.26a-b). During the first five minutes of flow the downwind slope of the model dome began to steepen almost immediately at the crest. The windward slope also steepened (eroded) and the sides began to widen (Photograph 7.4).



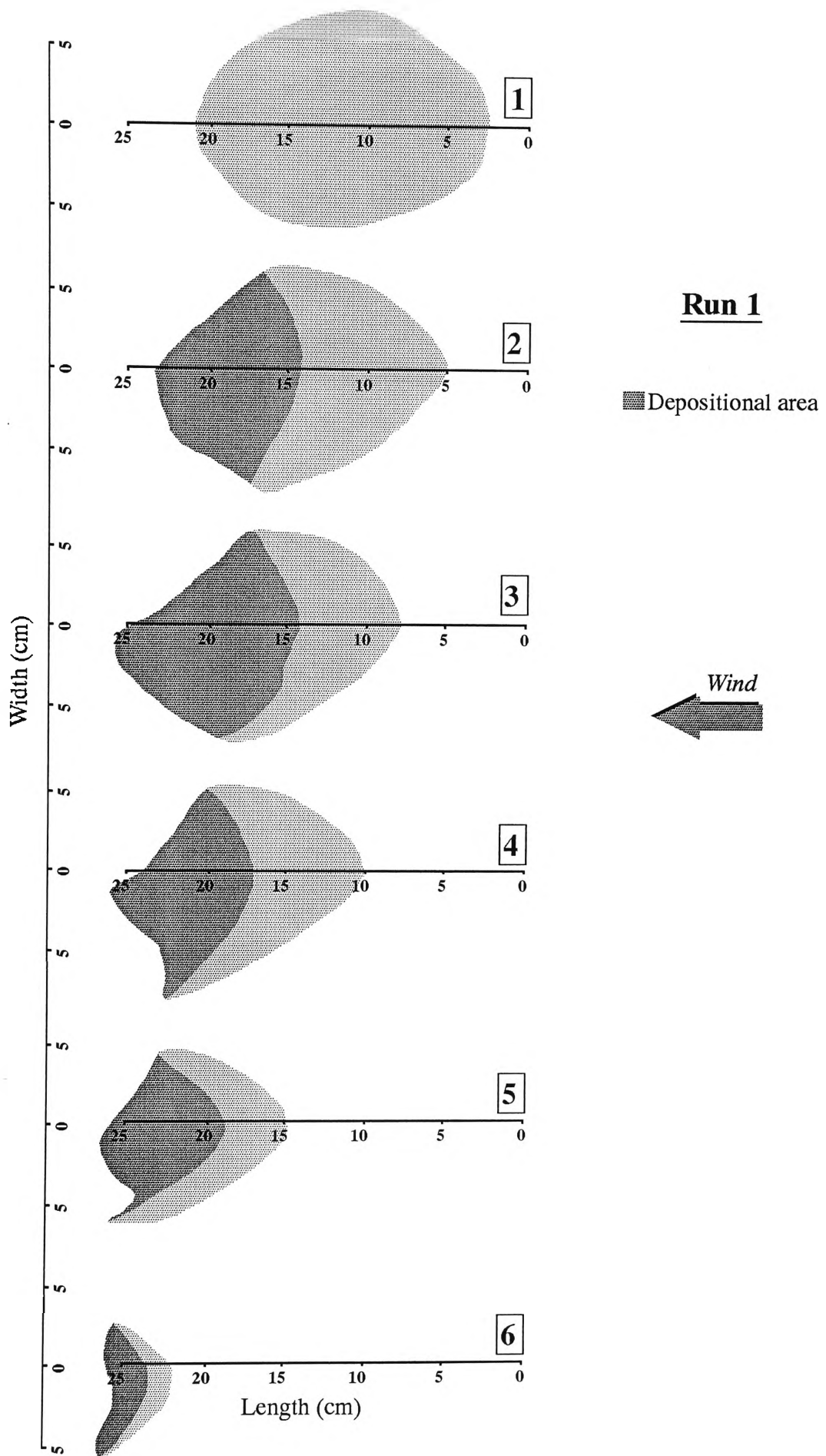


**Initial 'dome' shape prior to experiment**

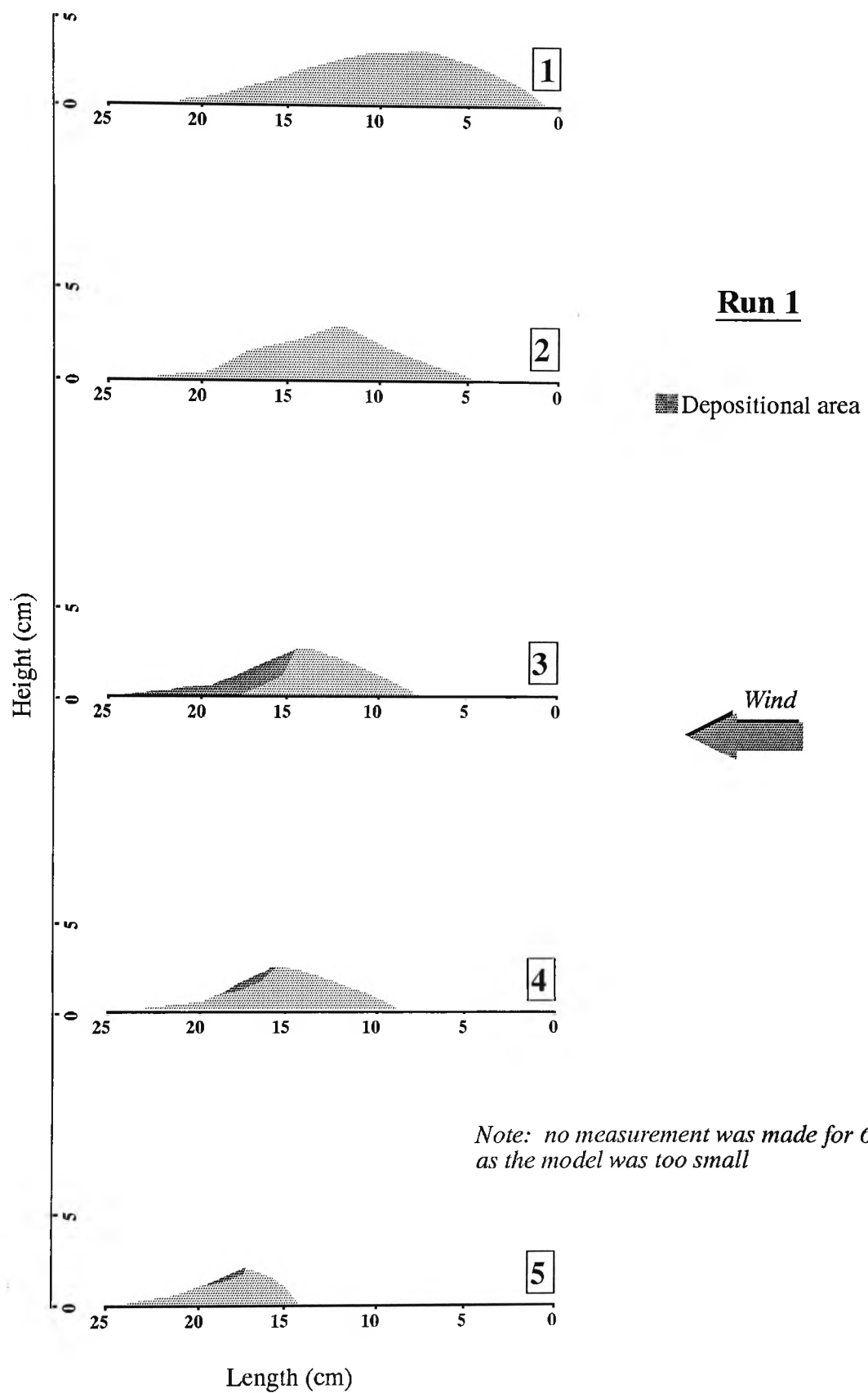


**Model shape, mid-way through the experiment**

**Photograph 7.4 Model shape before and during experiment**



**Figure 7.26a** Wind tunnel results, showing plan view



**Figure 7.26b Wind tunnel results, cross-sectional view**

Sand was blown up the windward slope and deposited on the lee side of the dune. Also apparent was a definite erosion/deposition delineation line as the lighter sediments were concentrated along the windward slope, with the darker, heavier sediments concentrated on the lee. The boundary of these areas (shown on the figures) continued to evolve over the length of the experiment as the area dominated by the darker sediments became smaller and the lighter sediments began to curve around the sides of dune. The model dune continued to steepen and at the conclusion of the experiment had decreased significantly in size and attained a rather 'boomerang' shape. Both the plan and cross-section views illustrate these changes.

Field observations were not made of flow divergence around the sides of the dune; however, the flow experiments conducted in both August and October, as discussed in the previous sections, did measure vertical flow structure associated with both a slipfaced and non-slipfaced slope, in an attempt to determine the evolutionary change from dome to barchan. These results will not be discussed again here, but in general, they indicate that over time, an equilibrium form (a non-slipfaced dune) will develop into a slipfaced form, due to a change in the balance between flow velocity and direction, sediment transport, and windward slope length and/or angle. The wind tunnel experiments are consistent with this hypothesis; the dome-shaped non-slipfaced form gradually begins to exhibit an increasingly asymmetric profile, with the "crest" of the dune migrating forward, as deposition increases downwind. Although no avalanching was observed, this was probably due to a lack of steady sediment supply, as the dune gradually decreased in size.

Field observations of the evolution of a dome dune to a crescent dune (or barchan) made by King (1918) as outlined in Chapter 2, indicate that the results of the wind tunnel experiments were similar to what he observed in a field situation. This was particularly true for Run 1, the most noticeable difference being the significant loss of sand volume of the experimental

dune as compared to the field example. This loss of volume was due to a lack of upwind sand supply. Although King did not specifically mention the role of volume fluctuations in the evolution from dome dune to barchan, from his diagram it appears that dune volume increased over the observation period, implying a steady sand supply was necessary for the complete evolution of a dome dune to a barchan. The design of the wind tunnel did not allow for the controlled input of sand, resulting in only a partial transformation from dome to barchan. In addition, scaling may have influenced the process; the tunnel was quite small, which required the model to be scaled down accordingly. It is unknown whether flow was significantly affected by the sides of the tunnel, affecting overall morphologic change. Despite these possible technical problems, the model exhibited changes similar to those observed as part of this thesis, and by other researchers.

## **Chapter 8**

### **CONCLUSION**

#### **8.1 REGIONAL WIND REGIME, WIND RESULTANTS, AND DUNE MOVEMENT**

Chapter Six presented the results of the analysis of the regional wind regime in the study areas. The Fryberger/Dean and Landsberg/Jennings methods were employed to determine the resultant sand transport potential and direction over the five-month study period. Both of these methods yielded similar results. The wind regime in both study areas is variable, with strong southwesterly seabreezes and occasional easterly storm winds. The sand roses (Chapter Six, Fig. 6.2 and 6.3) show that even though it is possible to calculate the resultant drift potential and direction, this resultant may not reflect the actual wind variability or net sand drift direction over a short period of time, or over a small area.

The wind resultants calculated for the study areas correlate reasonably well with the measured displacement directions (Chapter Four). Given the differences in both grain size and density characteristics, potential sediment sources, exposure to sand transporting winds, and dune size, possible wind instrument error, the relationship between the resultant drift direction and dune displacement is acceptable.

The degree of slipface development for all the dunes was compared to the resultant drift direction. During the high intensity easterly winds, the Swakopmund dunes developed a slipface, whereas the Walvis Bay dunes did not. During low intensity/high frequency events, all dunes developed a slipface, implying that either type of event (i.e. high or low intensity) may equally facilitate slipface development and significant morphologic change.

Based on the irregular morphology exhibited by the dunes over most of the study period, a new classification scheme was introduced. This scheme recognizes two 'transitional' dune types, a transitional dome and a transitional barchan. These types are 'transitional' because they exist as part of the dome to barchan evolutionary sequence. These forms have (apparently) not been recognized by previous studies (Finkel, 1959; Hastenrath, 1967). These forms are recognized as distinct because in the case of the Namib dunes, they maintained their irregular form over most of the study period, which constitutes almost half a year. The irregular wind regime in the area allows these dunes to maintain this form, and not evolve into a barchan. Should the winds stay uni-directional over time, the evolutionary process will continue and a barchan will usually develop.

## 8.2 DUNE HEIGHT, DISPLACEMENT, AND VOLUME RELATIONSHIPS

A computer analysis of dune volume provided an accurate measurement of dune volume, compared to previous methods (e.g. Norris, 1965). Dune displacement was also measured, using a weighted mean centre method, which took into account the 3-dimensional distribution of sediment over the dune. This method was used primarily because the irregular shape of the dunes did not allow displacement to be measured from the base of the slipface, the point of measurement employed by the previous studies outlined in Chapter Two.

Dune volume did not correlate with displacement in either study area. The Walvis Bay dunes, which exhibited marked size differences (based on volume calculations) migrated in proportion to their size, with the smallest dune (WB3) moving further than the largest dune (WB1). The Swakopmund dunes migrated less distance, due possibly to their higher bulk density than the Walvis Bay dunes, and also their limited exposure to sand transporting winds.

Chapter Five included height measurements for all dunes, which were compared to dune displacement. In all instances, there was no significant correlation between these variables. The height/displacement relationship (where a decrease in height results in an increase in dune displacement) has been accepted without question (e.g. Cooke et al., 1993). However, the results from the Namib dunes show that this is not always the case.

Dune shape may influence the relationship between dune height and displacement. The dunes used in previous studies were relatively symmetrical in shape, unlike the Namib dunes. Since the relationship between dune height and displacement is geometrical (Bagnold, 1941), assuming a relationship to exist for asymmetrical forms may lead to inaccurate conclusions.

The results of the dune height/displacement relationship indicates the potential problems of using dune height as an indicator of size. For example, during the 6-7 survey period, dune height for WB1 and WB2 increased but volume decreased. This implies a possible re-distribution of sediment over the dune, with a concentration at the slipface, where the height measurement was made. This correlates well with the model of dune evolution presented in the following section, particularly since the dunes were assuming a more barchanoid form at this time.

### 8.3 A MODEL OF DOME TO BARCHAN EVOLUTION

Figure 8.1 presents a schematic summary diagram illustrating the process of evolutionary change from a stable dome morphology to a barchan, based on velocity and sand transport data collected from the experiments conducted in Chapter Seven, and observations on dune migration, volume and morphologic change in relation to the regional and local wind regime presented in Chapters Four to Six.



### 8.3.1 The Model

This model is similar to Bagnold's (1941) observations of dune evolution and sand transport (Chapter Two). Although the model is similar, it attempts to address certain aspects of slipface formation and 3-dimensional morphologic change not adequately explained by previous research. In addition, the model also incorporates the 'transitional' dune types described in Chapter Six, which form part of the evolutionary sequence from smooth slope (dome) to slipface slope (barchan) in uni-directional wind regimes. The representative dune forms used as examples in the model are taken directly from survey data, with the exception of the dome, which is drawn from the photograph included in Figure 2.3. The steps in the model have been limited to four, although several intermediate steps may be assumed to exist, but are not illustrated here.

#### 8.3.1.1 Stage 1: Initial Dome Shape

A dome represents a stable, equilibrium form, based on erosion/deposition processes and wind velocity profiles. Overall shape is relatively symmetrical; the erosional area of the dune is virtually equal to the depositional area, which not only results in a symmetrical dune profile, but also uniform velocity profiles across the dune, where velocity increases at regular intervals up the windward slope, peaks at the highest point of the dune, and decreases uniformly down the lee slope (Chapter Seven, Fig. 7.12 and 7.13). Erosion occurs up the windward slope; sediment is carried through the transportational area (highest point of the dune) and deposited as velocity begins to decrease. By definition, a dome does not contain a slipface, due to uniform wind flow (with no flow separation) and sand transport.

Stage 1 of the model (Fig. 8.1) illustrates a classic dome shape. The characteristics of this shape, as outlined above, are also summarized in Figure 8.1. This stable form cannot maintain

### Initiating Factors:

- increased sediment input
- short-term changes in wind direction

Wind  
4m/s



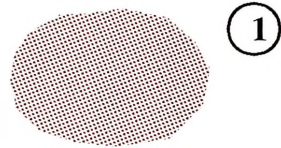
increasing wind velocity will accelerate process and will also lead to increased flow separation (see below)

### Transitional Forms

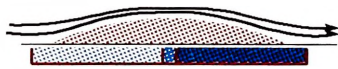
(these forms will be maintained over time under a bi-directional wind regime)

erosional area  
transportational area  
depositional area

Schematic Profiles



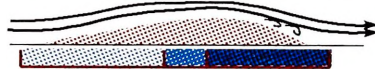
1



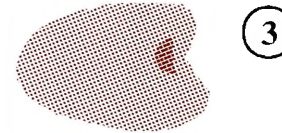
- relatively symmetrical morphology
- erosional area = depositional area
- no slipface
- no flow separation
- minimal flow divergence around sides
- represents an equilibrium form, based on sand transport and velocity profiles
- this equilibrium cannot be maintained, as wind variability over time will de-stabilize the form and may introduce outside sediment into the system



2



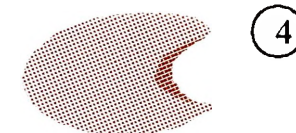
- profile becoming increasingly asymmetrical as sediment deposition over crest and lee slope area increases
- depositional area begins to shorten
- flow divergence continues around sides, although this has minimal impact on dune form
- flow separation becomes noticeable; this also facilitates deposition
- flow compression and acceleration over crest increases with increasing profile asymmetry, as height increases
- disequilibrium profile, as deposition begins to outweigh erosion on windward slope; velocity profile indicates slightly decreasing velocity over lee slope



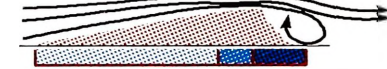
3



- flow separation marked
- separation evident
- depositional area shortens
- significant deposition at dune crest and over lee slope, due in part to steepening and avalanching, but also increasing sediment movement up the windward slope resulting from flow acceleration as streamlines are compressed and carrying capacity is increased
- flow separation and acceleration over lee slope results in significant deposition
- flow divergence and acceleration due to horizontal compression leads to increasing sediment erosion and deposition (horns) around sides



4



- slipface fully developed
- continuing process of flow acceleration - erosion - flow separation - deposition maintains form
- depositional area is minimal
- equilibrium form is maintained, as sediment transport is equalized both horizontally and vertically, i.e. horns allow excess sediment derived from outside to be shed from dune due to horizontal flow divergence - compression - acceleration
- although sand transport measurements and velocity profile indicates that this form is a 'disequilibrium' form, the [hypothesized] 3D flow structure indicates that the shedding of excess sediment via the horns, combined with the flow separation, deposition, and avalanching at the crest, suggest a state of equilibrium, as erosion/deposition over the windward slope and dune sides and over the crest and off the horns constantly adjust

## Characteristics of Form and Description of Process

Figure 8.1 Evolutionary model of dome to barchan

equilibrium over the long term, due to inherent variability in the wind regime. The degree of variability is site-specific; in many cases, uni-directional wind regimes exist for months, creating a reasonably stable environment, where domes and/or barchans may co-exist unchanged for a long period. However, as discussed in Chapter One (Fig. 1.3) and later in this chapter, the wind regime in the Namib is moderately variable (see Chapter Four, Fig. 4.4).

#### 8.3.1.2 Stage 2: Transitional Form (Transitional Dome)

The definition of transitional dome and transitional barchan forms was presented in Chapter Six. These dune forms were recognized as distinct from domes and barchans, due to their irregular morphology. These irregular forms were exhibited by all the Namib dunes at one time or another during the five-month study period. Based on the classification criteria presented in Chapter Six, only the Walvis Bay dunes exhibited true 'barchan' morphology, and at no time could the dunes in either study area be classified as 'domes'. Most of the time these dunes were either transitional barchans or transitional domes. The primary difference between these two transitional forms is the presence of a slipface. A transitional dome has an irregular morphology and does not contain a slipface, whilst a transitional barchan is also irregular in form but does contain a slipface. These forms are both considered part of the evolutionary process of dome to barchan, although variations in form may occur due to local differences in wind velocity and direction.

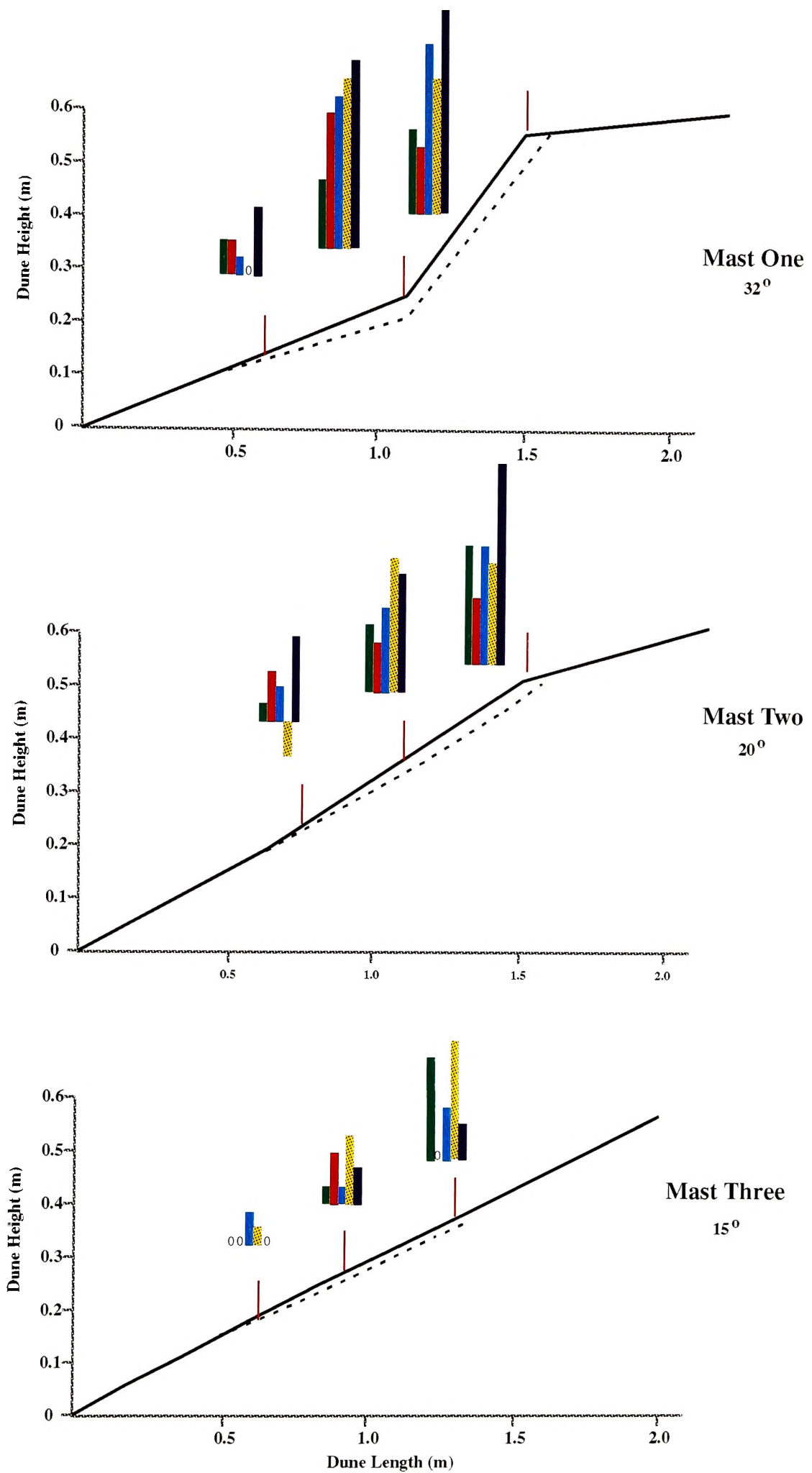
Stage 2 illustrates the first step in the process of evolution. Given a change in sediment supply or wind patterns, the dome will begin to assume an increasingly asymmetrical profile, as sediment deposition near the crest and the top of the lee slope begins to increase. Velocity profile uniformity is decreased. Flow acceleration due to streamline compression at the highest point of the dune represents the transportational area of the dune, where erosion ends and deposition begins. Immediately over this highest point, streamlines decompress as pressure

drops and velocity decreases rapidly. Sediment eroded and transported over the dune is deposited in this lower velocity area, which is near the dune crest and continues over the lee slope. Height begins to increase with sediment build-up at the crest; windward slope erosion continues. The area of sand deposition begins to contract slightly in the downwind direction, although the amount of deposition is increasing relative to erosion. The increased deposition due to decreased velocity also begins to influence the flow. Flow immediately over the crest begins to separate to a small degree. The increasing asymmetry of the dune, due to deposition, produces an increase in leeward slope angle; should this angle exceed 16-20°, flow separation results (Fig. 8.2). Once separation is initiated, deposition becomes even more pronounced, due to the abrupt (as opposed to steady) decrease in velocity.

The change from smooth slope to slipface is an important process in the evolutionary model. As such it is important to identify, or attempt to identify, the initiating mechanism or conditions whereby a relatively smooth slope 'evolves' into a slipface.

The flow experiments (Chapter Seven) measured wind velocity over both a smooth 'dome' slope and one containing a slipface. This was done both across the dune from the lee slope to the windward slope (Experiments One and Two), where the lee slope contained both a smooth slope and a slipface, and also along the lee slope itself, where there was both a smooth slope and a slope containing a slipface (Experiment Three). The purpose of these experiments was to measure wind flow and sand transport over both slope types to observe the differences in these factors, and to see how these differences influence slipface initiation and maintenance.

From the results obtained from the flow experiments, and from observations of dune morphologic change over the five-month study period, it is possible to identify three important factors which influence the development of a slipface. These are wind velocity/direction, sediment supply, and windward slope length.



**Figure 8.2 Erosion and deposition over three slopes, Experiment Three**

Experiments One and Two demonstrated that at higher wind velocities, flow separation increases. In addition, Experiment Three showed that the lee slope can maintain an angle of up to  $20^{\circ}$ , with the corresponding velocity profiles showing no apparent flow separation. At higher wind velocities, erosion increases over the windward slope, leading to a greater rate of deposition near the top of the lee slope. This greater deposition may ultimately lead to an increase in dune height at the point of deposition, which increases slope angle at this point. The area of deposition decreases without a corresponding decrease in the amount of deposition, a situation which must lead to increasing dune asymmetry, particularly if the toe of the windward slope remains stationary, as it did during Experiment Two. This profile asymmetry is a precursor to slipface development, as indicated by observations of dune height and volume relationships (Chapter Four) whereby dune height increases in conjunction with a decrease in volume, implying a re-distribution of sediment across the dune and increasing asymmetry in a downwind direction.

Further evidence for sediment re-distribution is provided by SW2 and SW3. Subsequent to the July easterly storms, these dunes had aligned *en masse* in a westerly direction, but had not developed a slipface. However, with the onset of further easterly winds in August, both these dunes had developed a westerly-aligned slipface, implying that the previous easterlies had created an asymmetric dune profile which required further easterly winds for a full slipface to develop. Although the August winds had an easterly resultant drift direction (RDD), they were low intensity/moderately variable winds, not sufficient to facilitate slipface development without prior westerly dune alignment.

Both Experiments Two and Three demonstrated that a slipface developed on the lee slope when the associated windward slope length was relatively shorter, compared to the windward slope length associated with a lee slope where a slipface had not developed. Experiment Three showed that the windward slope decreased in length and increased in angle as the associated lee

slope went from a smooth slope to a slipface and that deposition also increased incrementally from smooth slope to slipface (Fig. 8.2).

A comparison of the morphological development of WB1 and WB3 shows that sediment supply does not appear to strongly influence slipface development. WB1, under uni-directional winds, contained a slipface for a greater amount of time than did WB3, and also exhibited an overall increase in volume. This volumetric increase implies an influx of sediment to the dune. WB3 exhibited an overall decrease in volume over the study period, and developed a slipface for a short time. This slipface development occurred despite a relatively low height (~0.6m). Bagnold (1941) recognized that "a certain minimum height must be attained before a permanent slipface may be established" (p. 203). Without a qualification of 'permanent' it may be assumed that this minimum height is less than 0.6m, based on the WB3 slipface development.

Based on the above conditions recognized as necessary for slipface development, it is hypothesized that a dome will not evolve into a barchan (i.e. develop a slipface) under low-velocity winds, and when slopes are long and low in height. However, over time even a dune exhibiting these characteristics will eventually develop a slipface and evolve into a barchan. This will happen when winds are uni-directional. It is therefore possible that a dome will remain a dome only if winds conditions are bi-modal, which would arrest the evolution of a smooth slope to a slipface, and begin the evolutionary process in the opposite direction.

The evolutionary model assumes a primarily uni-directional winds, but also accounts for localized variability which may have a direct effect on overall dune morphology and slipface development, as demonstrated by the Namib dunes. Variability in wind direction accounts for the 'transitional' forms exhibited by the Namib dunes which are included as part of the evolutionary model.

### 8.3.1.3 Stage 3: Transitional Form (Transitional Barchan)

Stage 3 presents the next phase of morphologic change and adjustment, as flow separation becomes marked. Slope adjustment to the increased deposition and flow separation over the lee slope is evidenced by the presence of a slipface. Continual avalanching at the brink allows the slipface to maintain a (stable) angle of repose ( $32^{\circ}$ - $34^{\circ}$ ). Continued erosion up the windward slope and deposition at the crest and over the lee slope require constant slope adjustment to this increasing sediment input, which is now facilitated by flow separation.

At this point, it is necessary to discuss the flow patterns around the sides of the dune. Although it has not been discussed in detail in this thesis, it must be emphasized that the flow is 3-dimensional over the dune form. Velocity data collected as part of these experiments represents a cross-sectional view of dune profiles and the velocity and depositional patterns at that point. It is reasonably acceptable to extrapolate these results to a 3-dimensional situation; however, flow divergence around the sides of the dune becomes a significant factor in equilibrium profile development and maintenance of a barchan. It was not within the scope of this thesis to look in detail at flow structure in this area of the dune. However, it is nonetheless possible to hypothesize on velocity patterns and sediment transport, based on the experimental data, and the conceptual model of evolution. In addition, the results of the wind tunnel experiments included in Chapter Seven also indicate that velocity increases around the dune 'horns', based on the development of these 'horns' over time.

Flow separation over the dune crest primarily occurs as vertical separation, while that which occurs around the sides of the dune is primarily horizontal flow separation. Flow divergence around the sides of the dune occurs simultaneously with flow over the dune itself. Once the dune reaches the point where vertical flow separation is pronounced, horizontal flow separation



also becomes significant, typified by the classic 'horn' development characteristic of stable barchan forms. In the horizontal flow separation, velocity diverges around the dune sides and flow is compressed and accelerated, with corresponding sediment erosion and transportation around the edges of the dune. Much of this sediment continues to be transported off the dune, as velocities do not significantly decrease. This steady velocity enables the sides of the dune to migrate at a faster rate than the bulk of the dune (Howard, 1978; Bagnold, 1941). These horizontal streamlines closely follow the contour of the dune; when they meet the vertical streamlines, there is a sudden reduction in velocity over a small area, as pressure is reduced, in the same fashion as vertical flow separation occurs over the dune crest. With the onset of vertical flow separation, the velocity in the 'separation envelope' is greatly reduced. This zone of reduced velocity, and low pressure, interacts with the horizontal streamlines, effectively reducing velocity sufficiently so that deposition results. This minor deposition occurs in the form of 'horns'. The vertical and horizontal streamlines rejoin downwind and flow once again becomes regular.

#### 8.3.1.4 Stage 4: Barchan Form

Stage 4 illustrates the final stage of the evolutionary process. The slipface is fully developed. Flow continues to separate over the lee slope and around the horns, and deposition continues. The dune advances as the process of erosion from the windward slope and deposition on the crest and upper lee slope leads to avalanching. The depositional area is now greatly reduced relative to the erosional area. This stable form is maintained as sediment transport and velocity are equalized both vertically and horizontally. The principle of continuity is maintained, as external sediment obtained from adjacent (upwind) sources is either shed off the dune horns, or deposited at the crest and lee slope. Flow separation over the lee slope allows this process to continue. The slipface accommodates the additional sediment by periodically avalanching to maintain a stable slope.

As mentioned previously, this process assumes a uni-directional wind maintaining steady threshold velocity. Although wind patterns may indeed remain 'stable' over a reasonable time, they are inherently dynamic, which ultimately leads to the instability (disequilibrium) of the dune form. If wind direction remains relatively constant, but velocity increases over time, the effect on the evolutionary process is that the change from dome to barchan is accelerated. The flow experiment and sand transport data (Chapter Seven) have shown that flow separation occurs to a greater degree at higher velocities, leading to the more rapid formation of a slipface and ultimately a faster return to a stable form, i.e. a barchan.

Variability in wind direction presents a more complicated effect on the dome to barchan evolutionary sequence. In areas where uni-directional winds exist on a seasonal basis, i.e. over several months, and where high velocity opposing (storm) winds also occur over a reasonable length of time, the resulting dune forms are quite complex. This is the case with the Namib dunes for the five-month survey period. The data presented in previous chapters demonstrates that these dunes maintain a disequilibrium, or 'transitional' morphology for several months.

### 8.3.2 Dune Shape and Crest/Brink Separation

Additional evidence for the evolutionary model is provided by the degree crest/brink coincidence exhibited by both the Walvis Bay and Swakopmund dunes. The crest/brink coincidence exhibited by the Walvis Bay dunes was greater than for the Swakopmund dunes. As discussed in Chapter Five, the degree of variation in the coincidence of slipface height and dune height (or crest/brink coincidence) is often taken as an indication of dune 'maturity' (Cooke et al., 1993), or 'equilibrium'. This implies an evolutionary relationship exists between a dome (with extreme crest/brink separation) and a barchan (with extreme crest/brink coincidence).

## 8.4 CONCLUSION

This thesis has presented the results of dune displacement measurements, volume calculations, and wind flow experiments for six dunes in the Namib desert, conducted over a five-month period. These analyses indicate that in more variable (i.e. less 'uni-directional') wind regimes, and where dune morphology and migration is measured regularly, i.e daily to monthly rather than twice in several years, dune morphology is quite variable, dunes do not always or often display simple geometric relationships between height, volume and displacement, and do not necessarily follow wind resultant transport paths.

The results of the study have led to the recognition of two new dune types, which form part of the dome to barchan evolutionary sequence. In addition, a model of dome to barchan evolutionary model was also developed, which utilized Bagnold's (1941) previous observations and also included velocity and sand transport measurements to quantify these observations. The experiments provided data which showed flow characteristics over a smooth, convex (dome) slope and over an asymmetric slope with a slipface (barchan), which was used in the development of the model. By collecting and incorporating additional data from areas which exhibit a variety of wind regimes and sediment characteristics, future research may allow further quantification of this evolutionary process.

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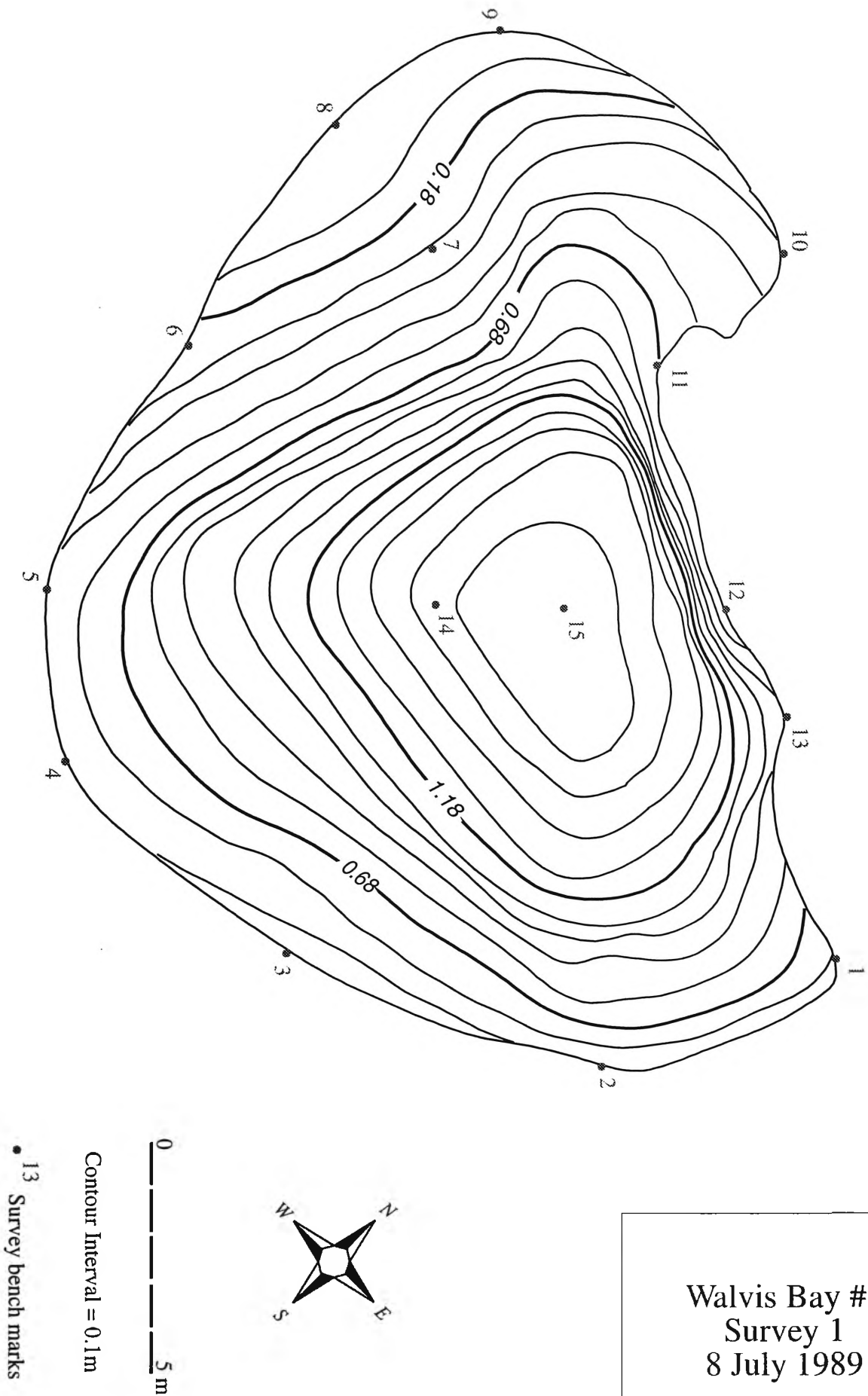
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# **APPENDIX I**

## **Contour maps**

Walvis Bay #1  
Survey 1  
8 July 1989





Walvis Bay #1  
Survey 2  
29 July 1989



0 ————— 5 m

Contour Interval = 0.1m

• 13 Survey bench marks

Walvis Bay #1  
Survey 3  
11 August 1989

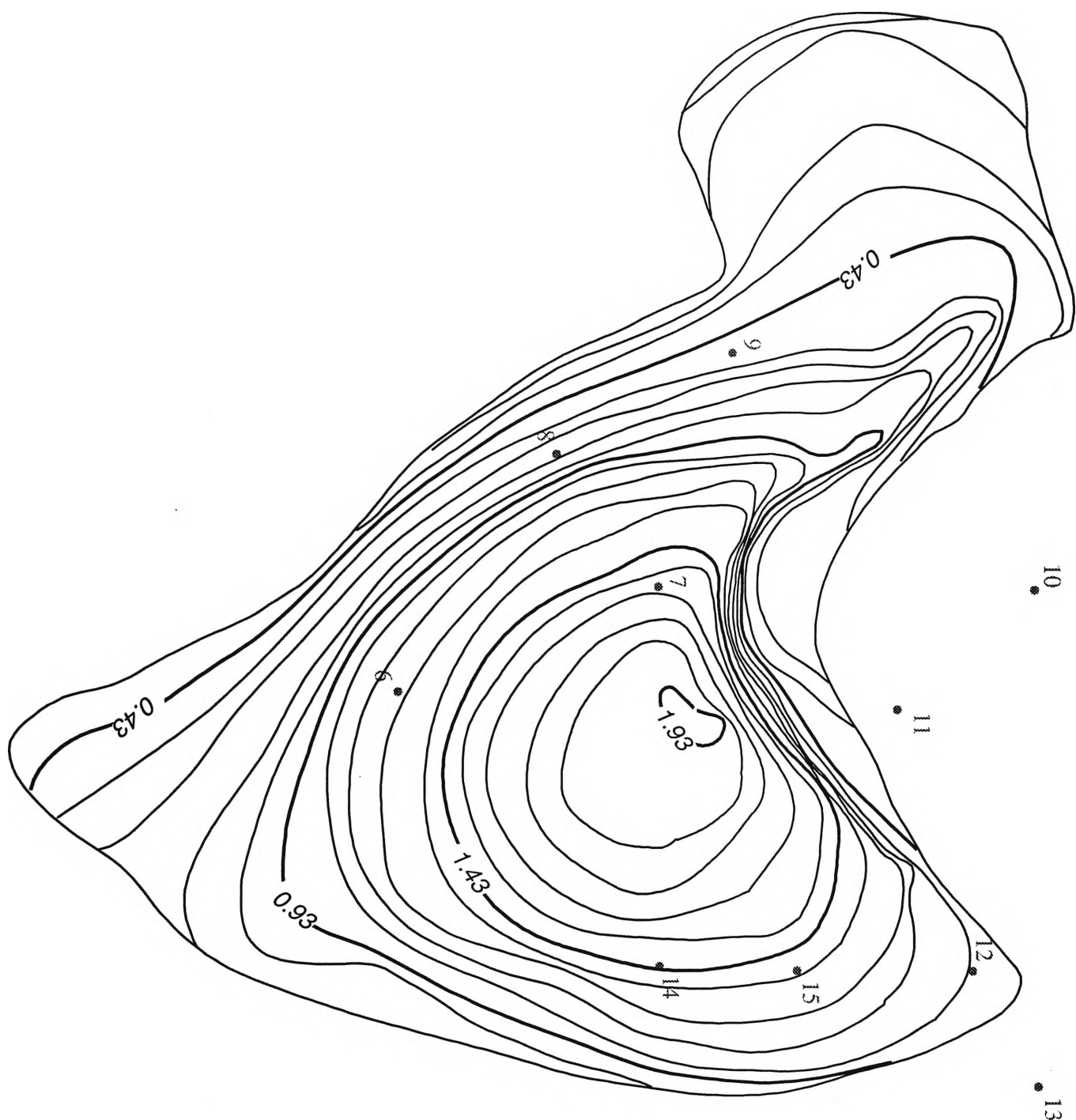


0 ————— 5 m

Contour Interval = 0.1m

•<sup>13</sup> Survey bench marks





Walvis Bay #1  
Survey 4  
29 August 1989

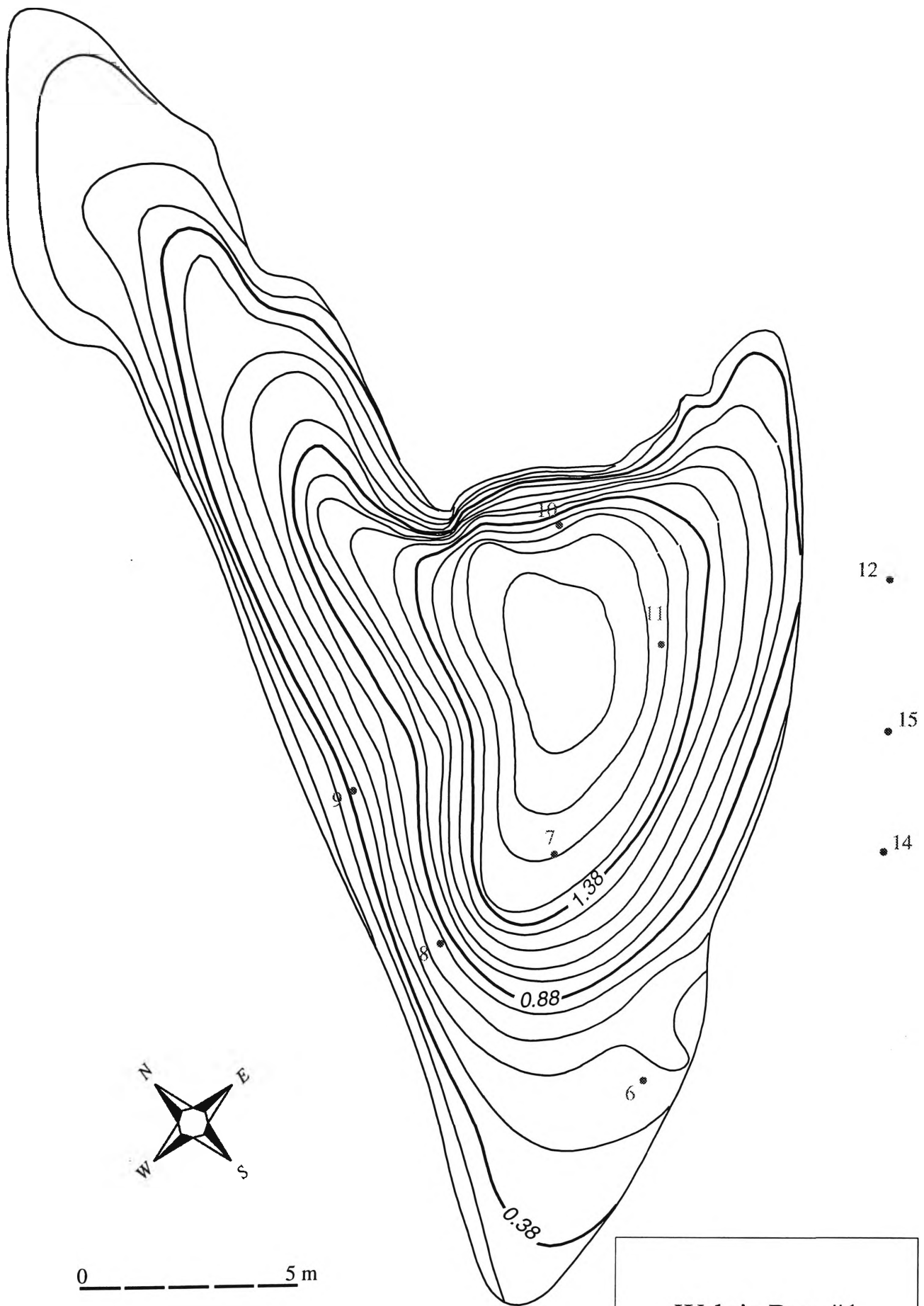


0 ——— 5 m

Contour Interval = 0.1m

• 13 Survey bench marks





0 5 m

Contour Interval = 0.1m

•<sup>13</sup> Survey bench marks

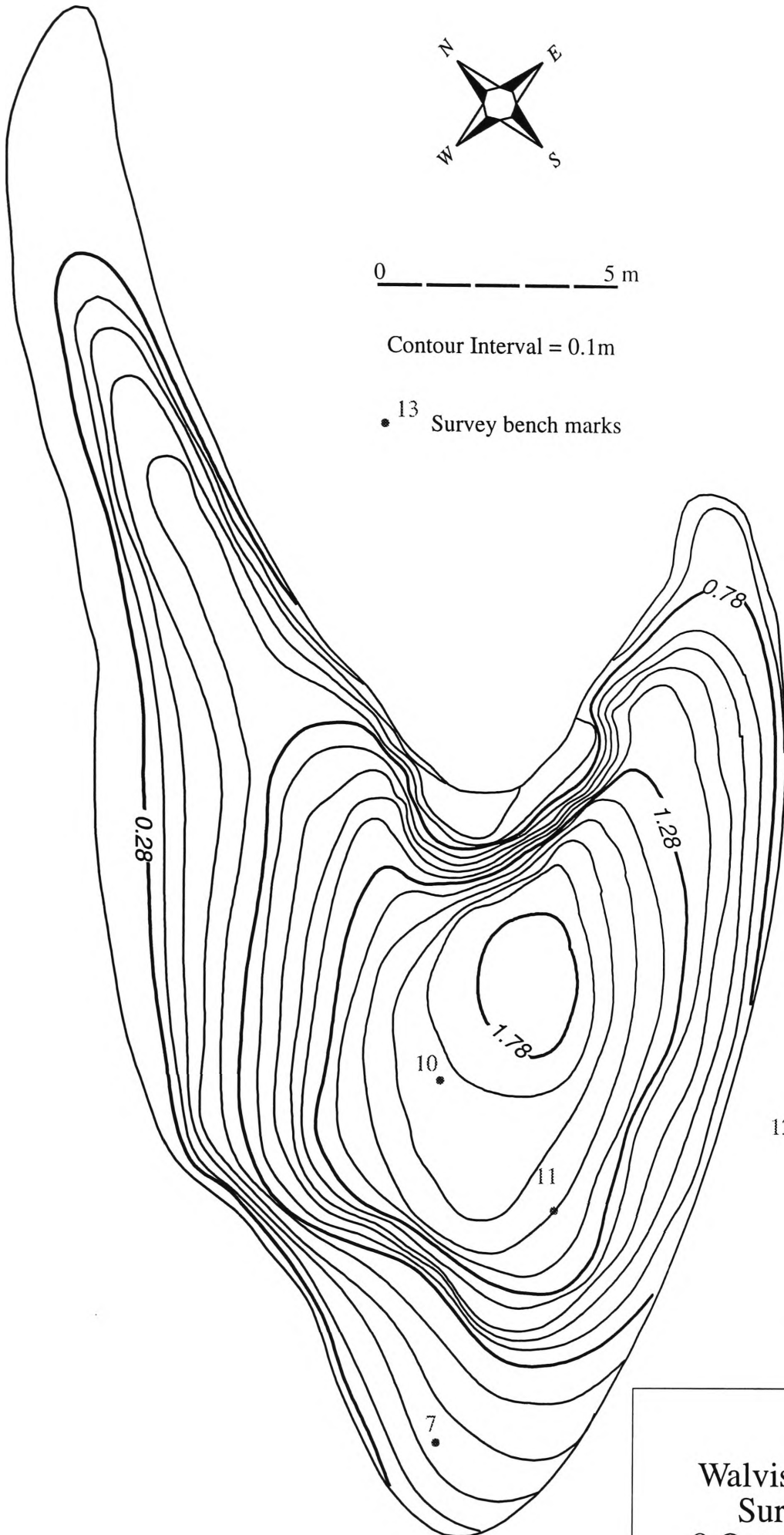
Walvis Bay #1  
Survey 5  
29 September 1989



0 ————— 5 m

Contour Interval = 0.1m

•<sup>13</sup> Survey bench marks



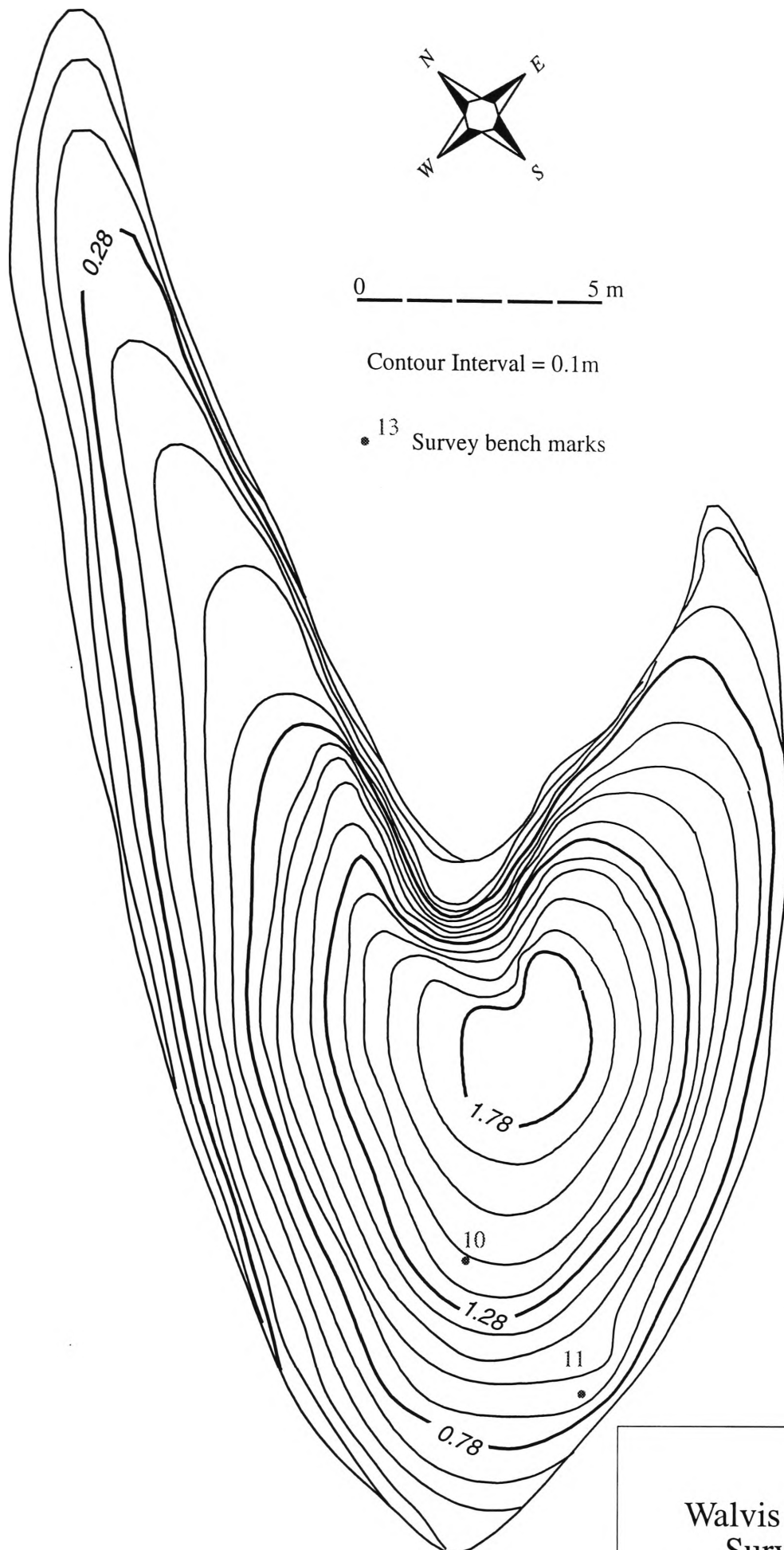
Walvis Bay #1  
Survey 6  
8 October 1989



0 ————— 5 m

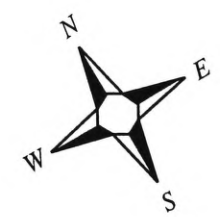
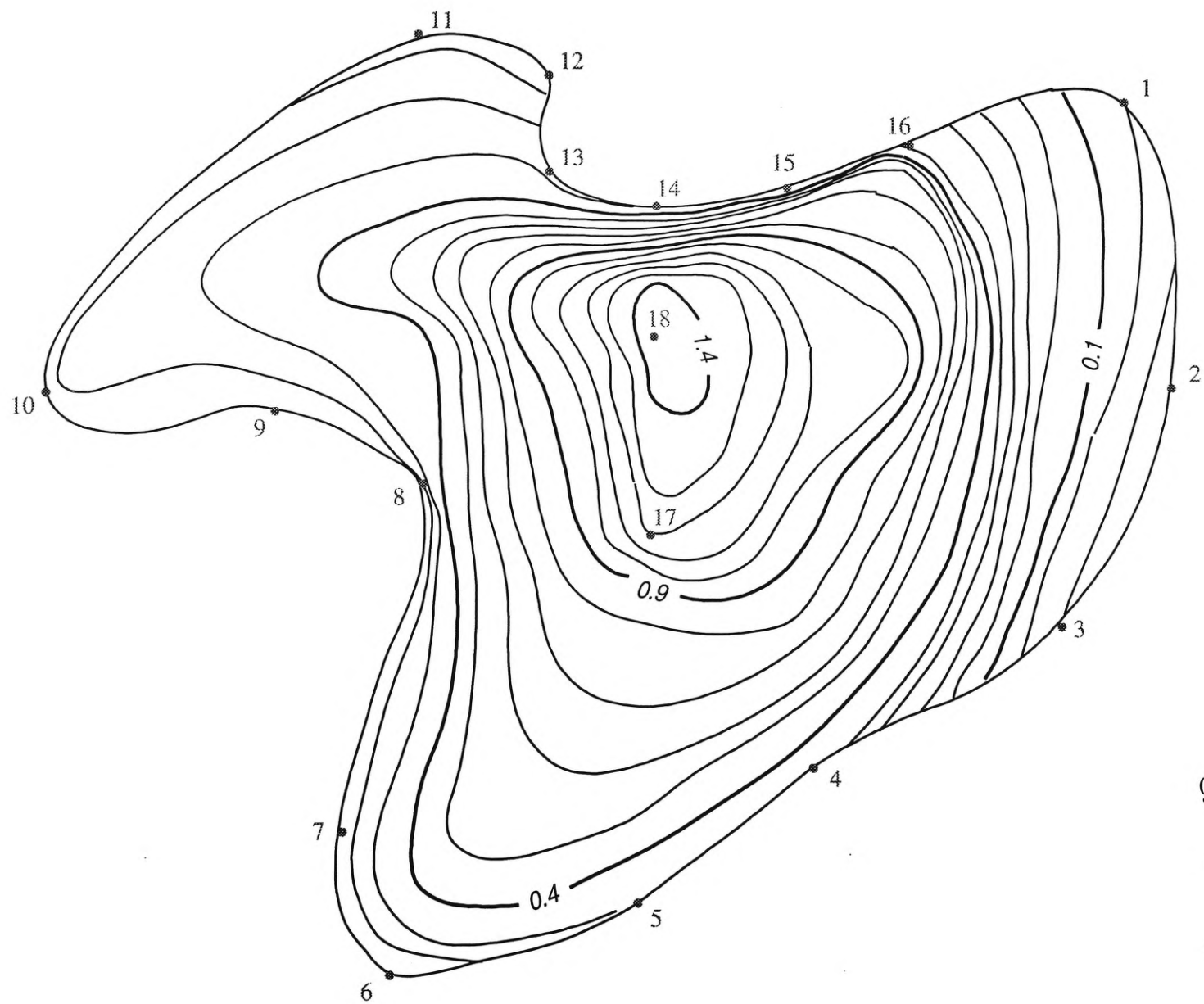
Contour Interval = 0.1m

• <sup>13</sup> Survey bench marks



Walvis Bay #1  
Survey 7  
20 October 1989

Walvis Bay #2  
Survey 1  
8 July 1989



0 ————— 5 m

Contour Interval = 0.1m

• 13 Survey bench marks

Walvis Bay #2  
Survey 2  
28 July 1989

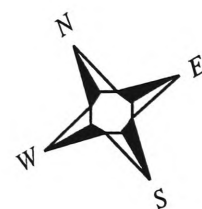


0 ————— 5 m

Contour Interval = 0.1m

•<sup>13</sup> Survey bench marks



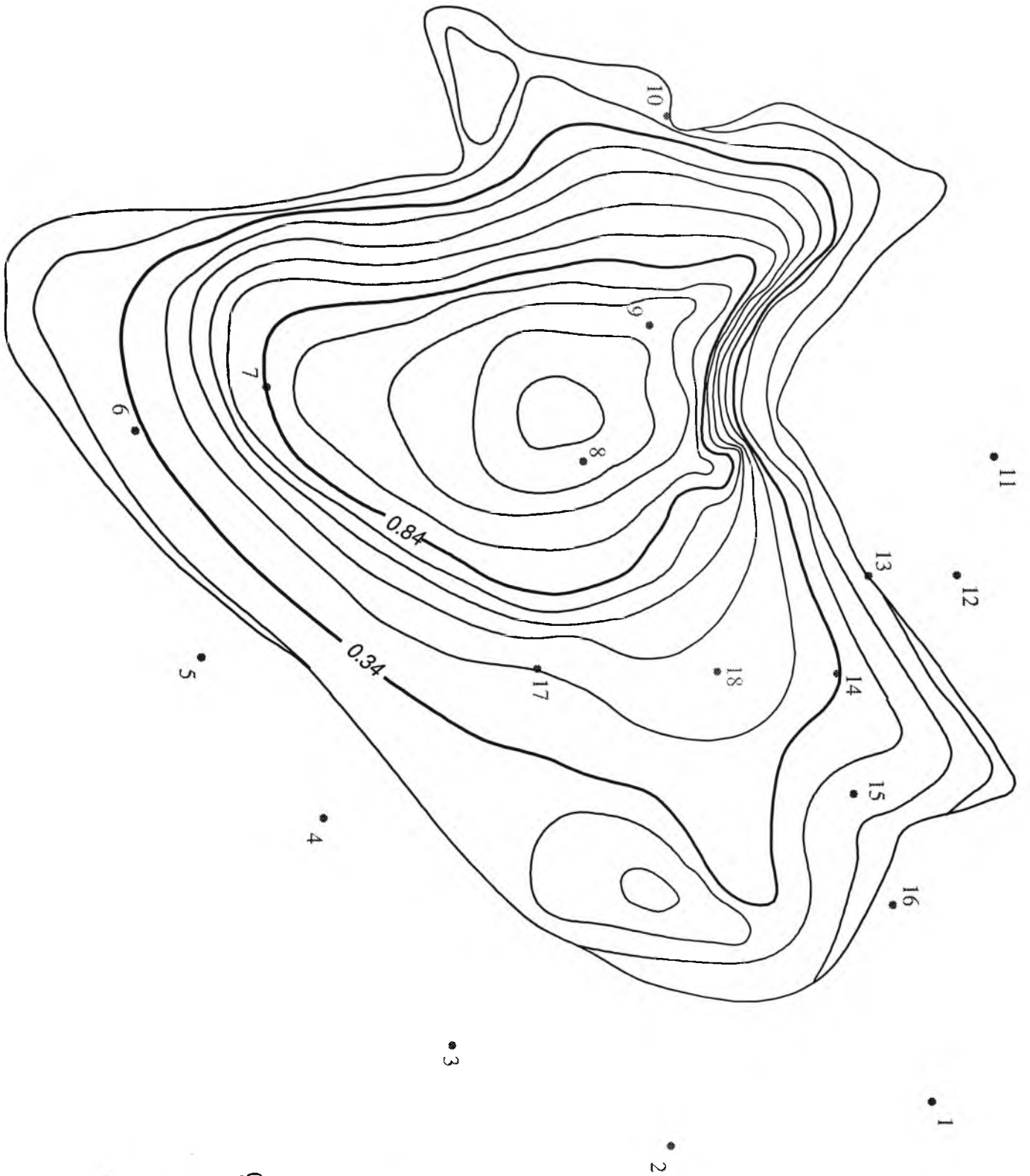


0 5 m

Contour Interval = 0.1m

•<sup>13</sup> Survey bench marks

Walvis Bay #2  
Survey 3  
11 August 1989



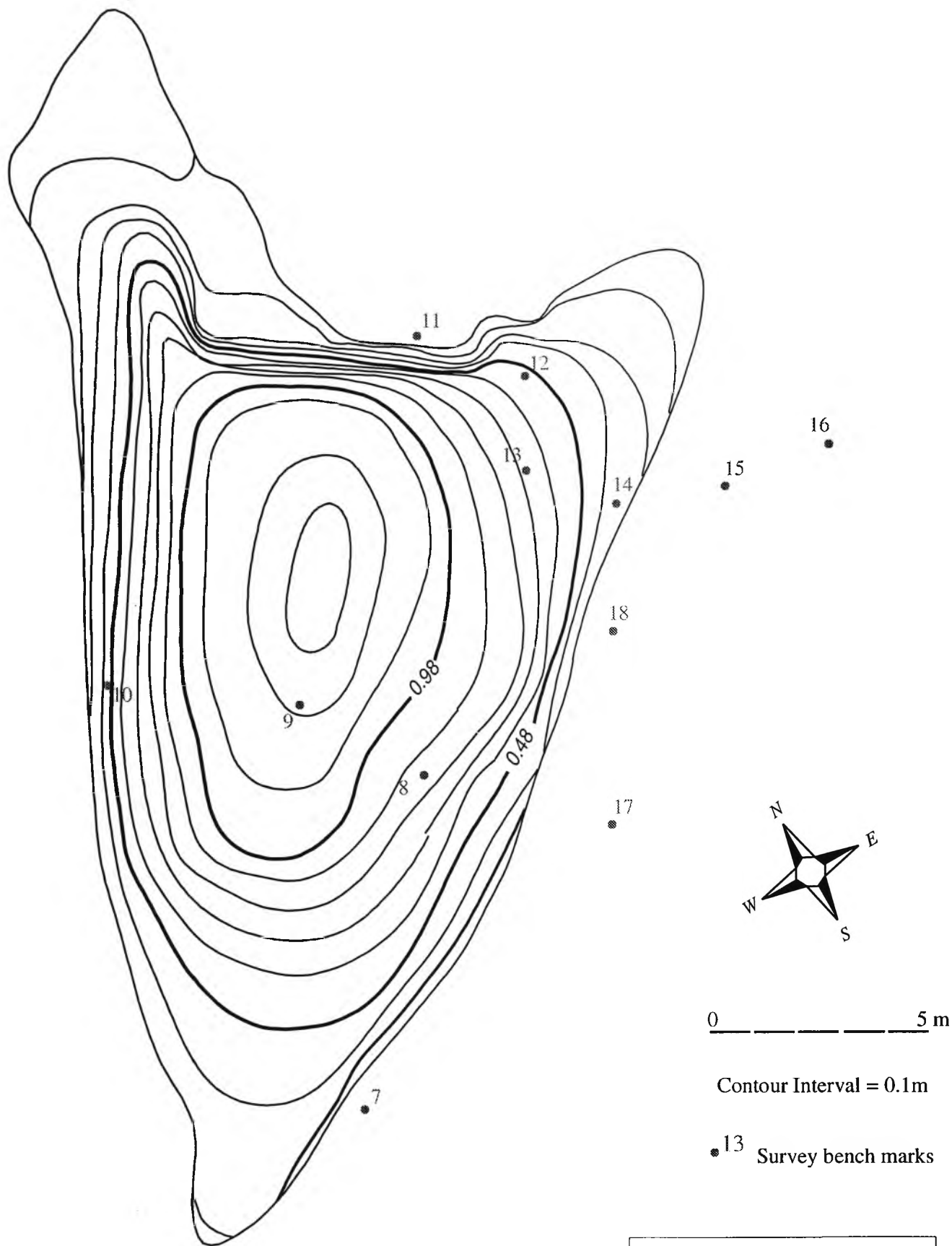
Walvis Bay #2  
Survey 4  
24 August 1989



0 ————— 5m

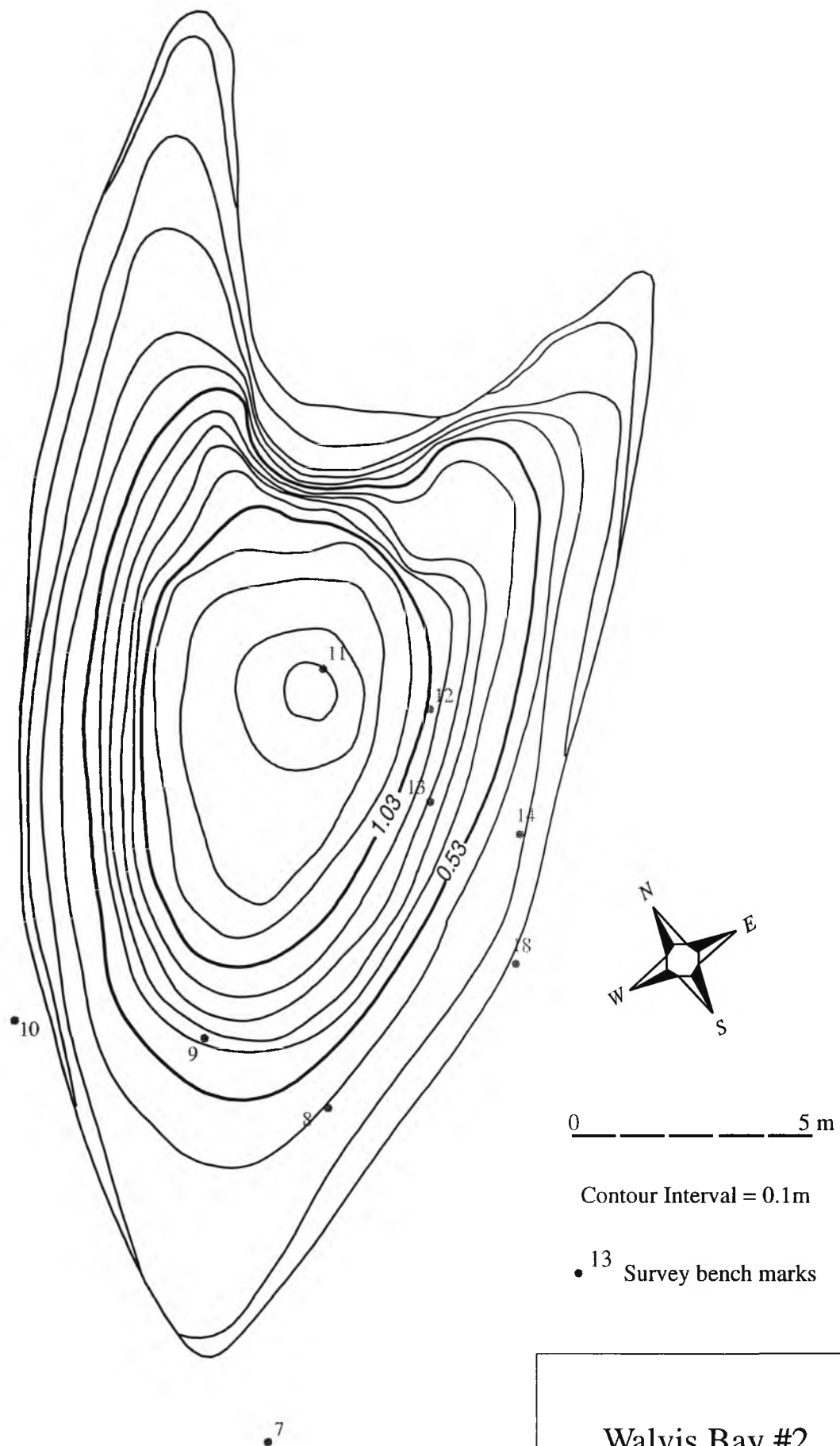
Contour Interval = 0.1m

• 13 Survey bench marks

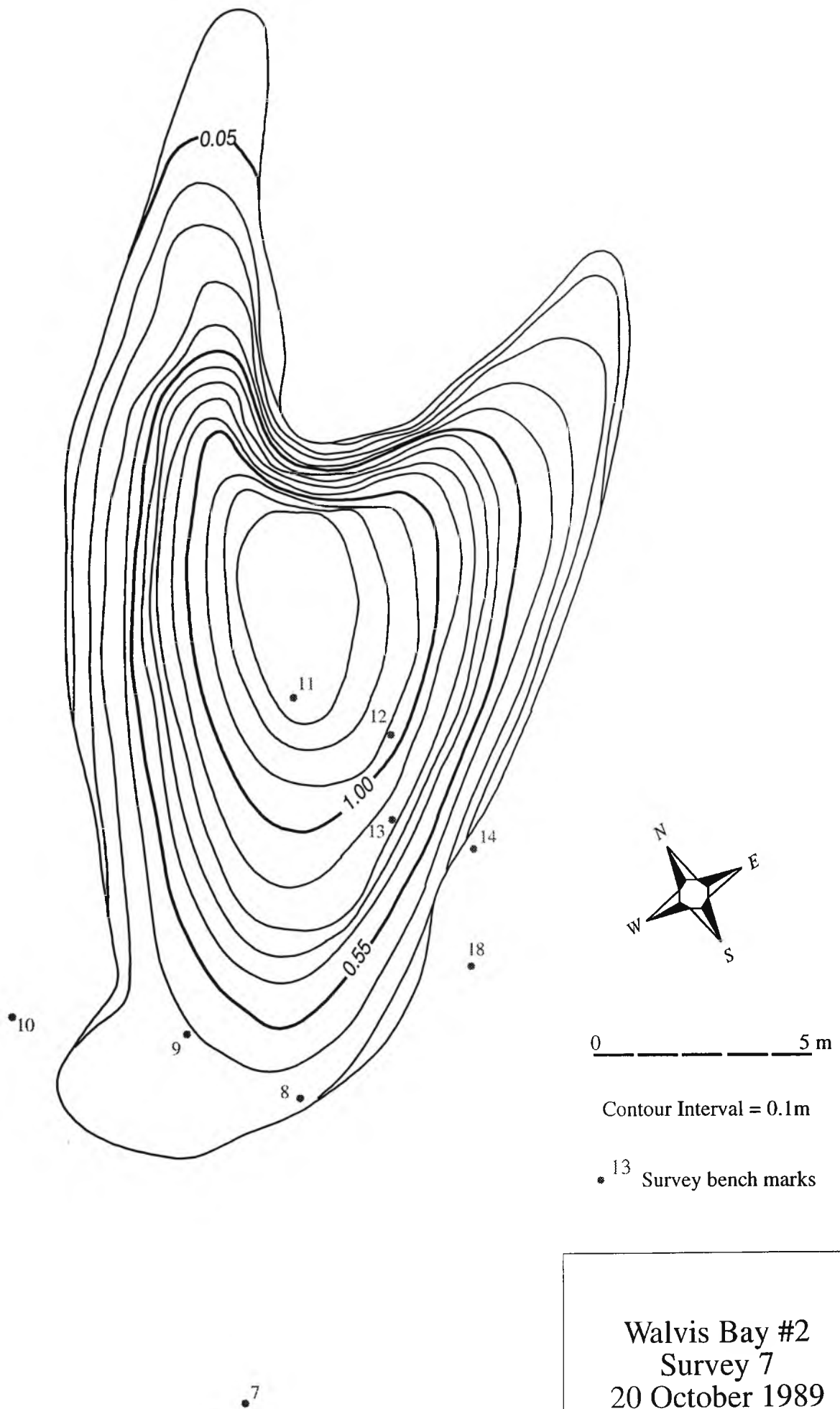


Walvis Bay #2  
Survey 5  
19 September 1989

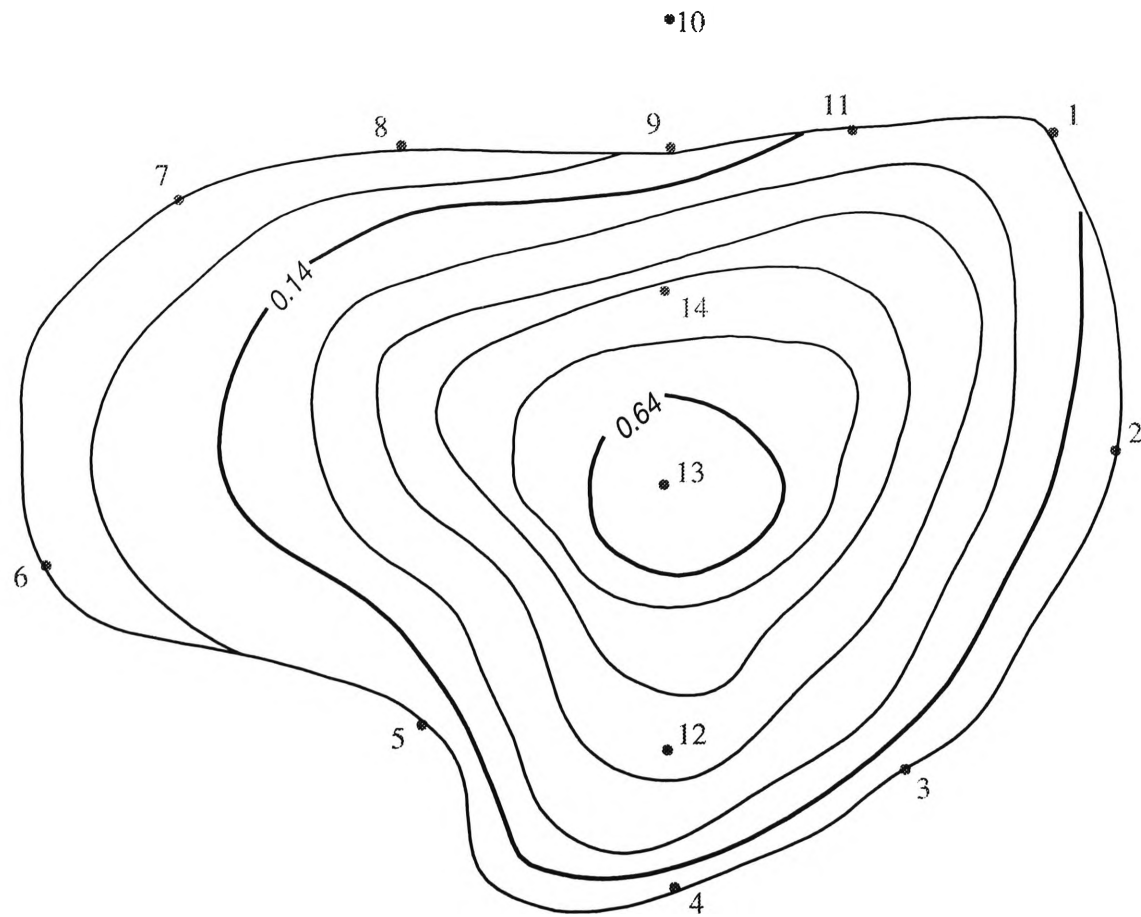




Walvis Bay #2  
Survey 6  
8 October 1989



Walvis Bay #3  
Survey 1  
8 July 1989

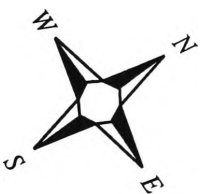
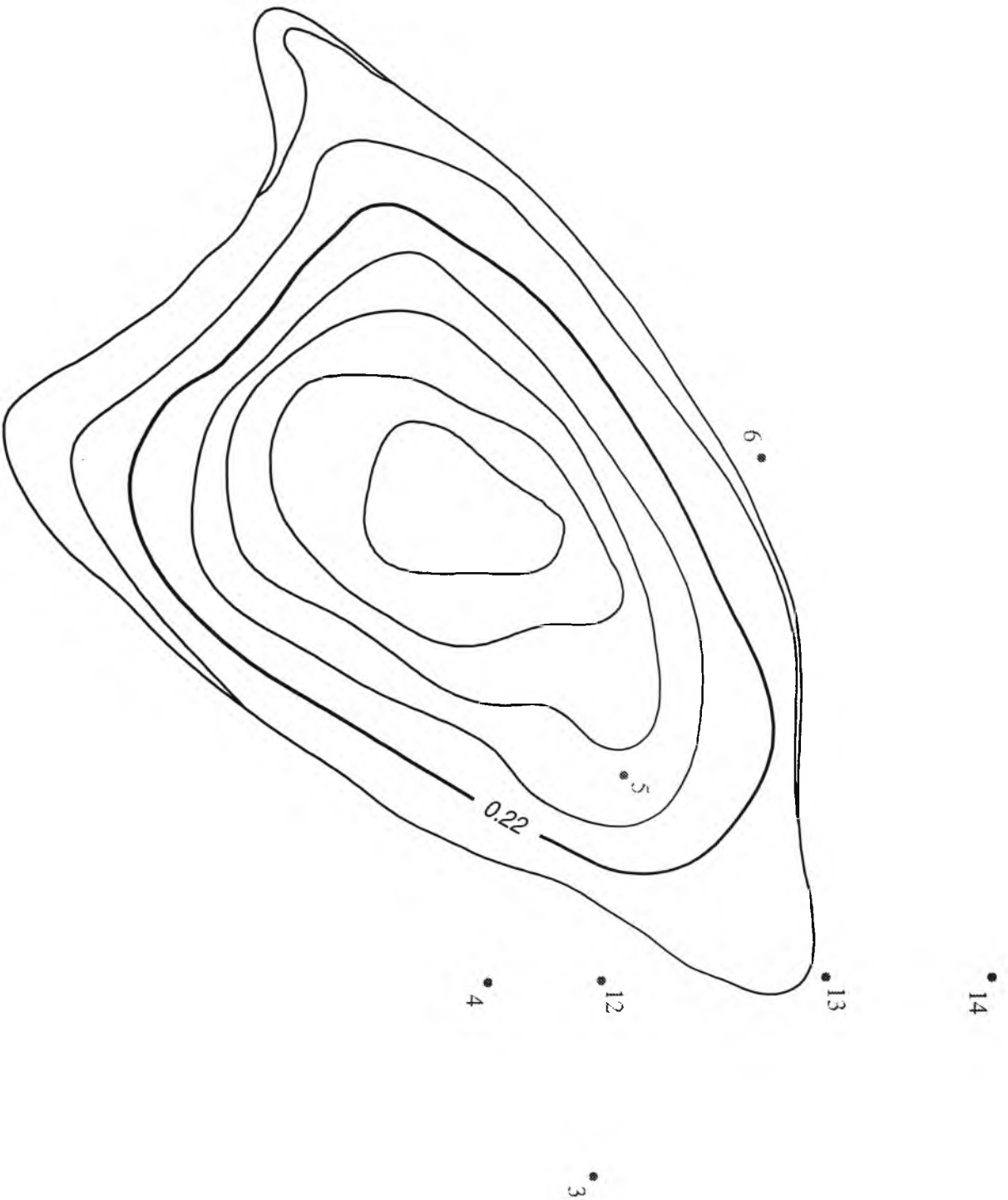


0 5 m

Contour Interval = 0.1m

• 13 Survey bench marks

Walvis Bay #3  
Survey 2  
29 July 1989

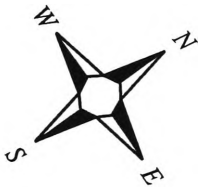


0 ————— 5 m

Contour Interval = 0.1m

• 13 Survey bench marks

Walvis Bay #3  
Survey 3  
12 August 1989

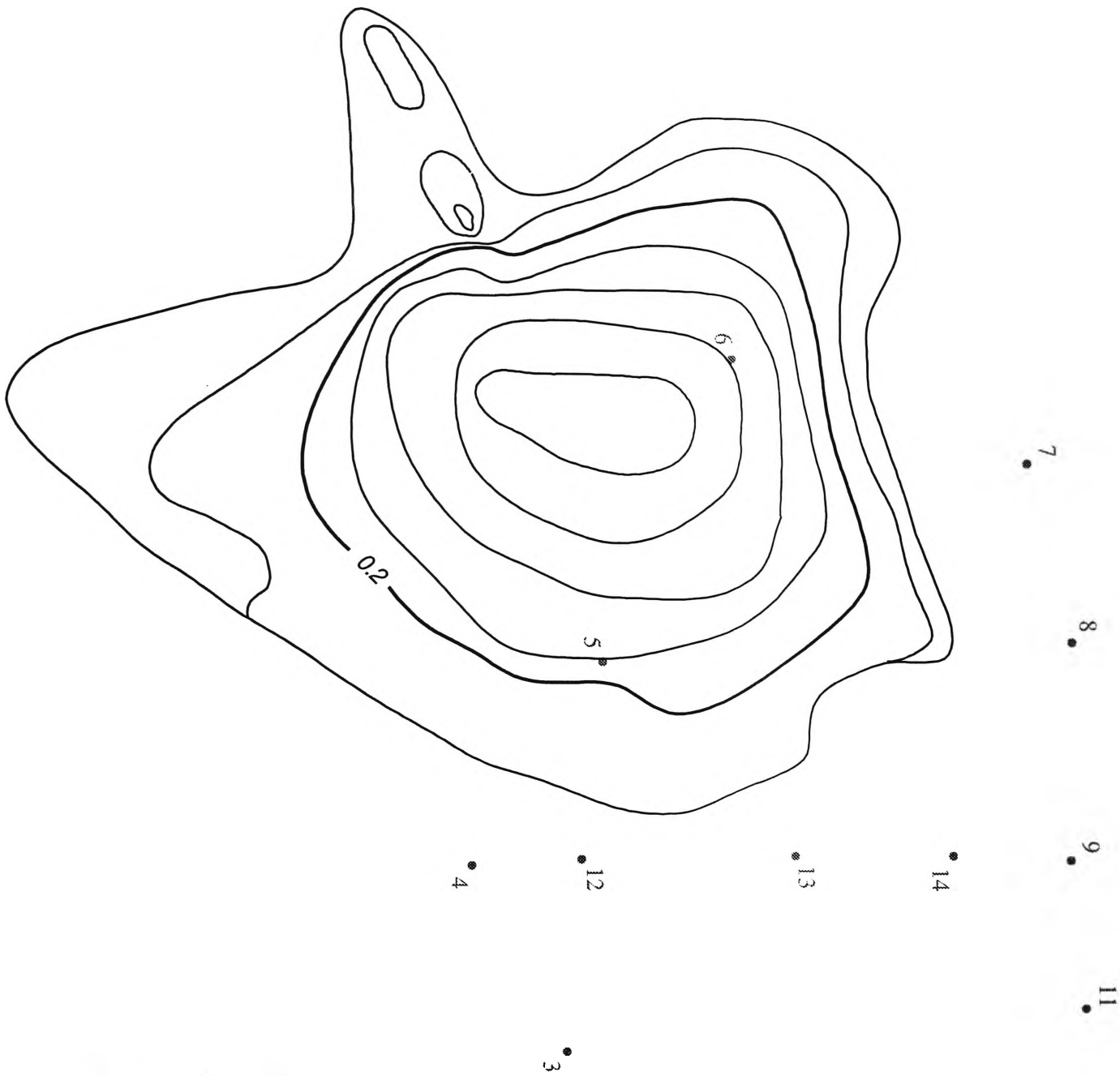


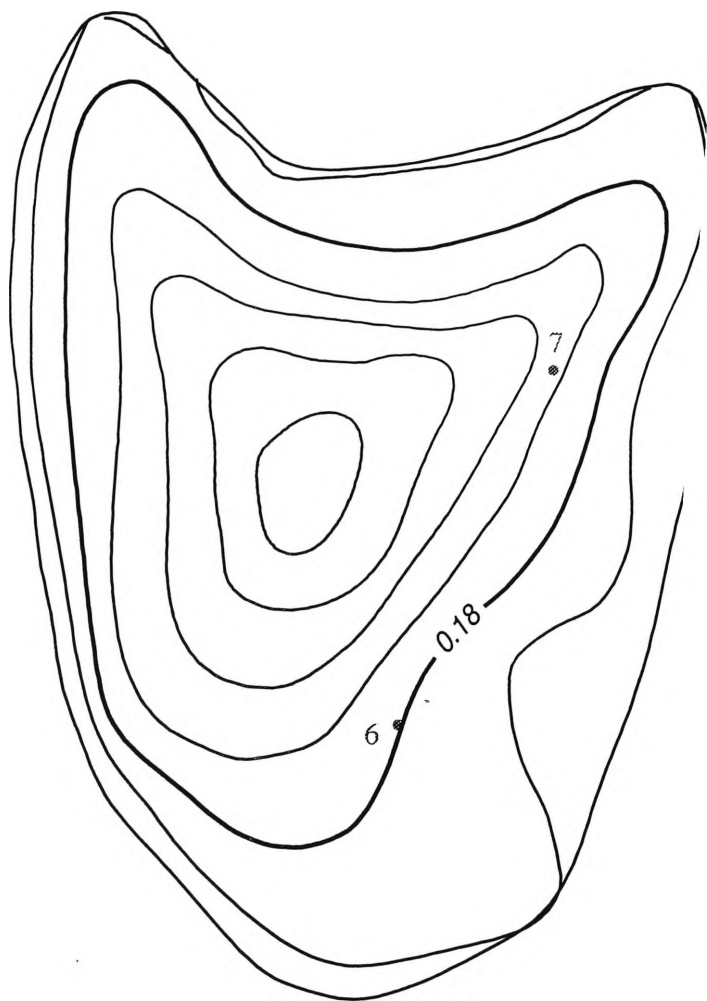
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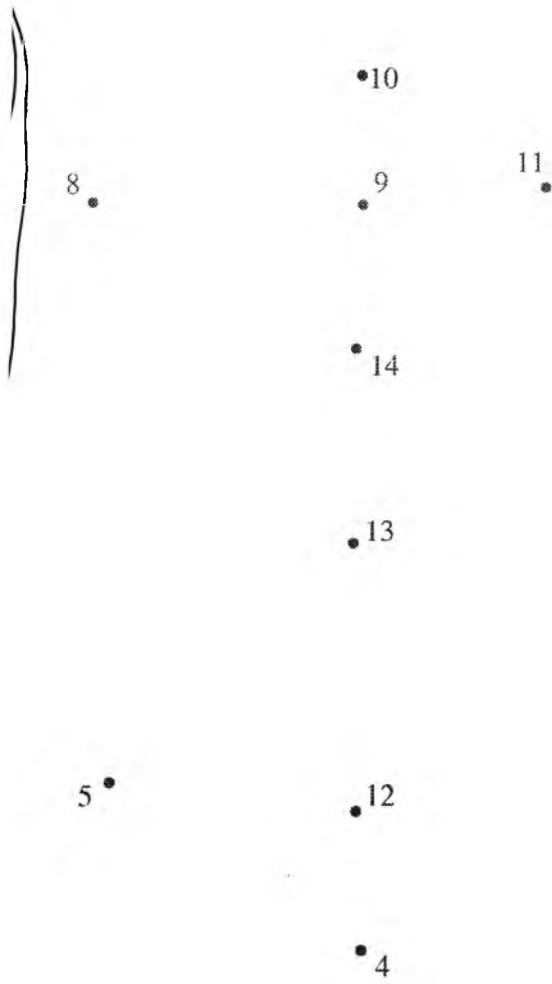
• 13 Survey bench marks

Walvis Bay #3  
Survey 4  
24 August 1989





Walvis Bay #3  
Survey 5  
19 September 1989



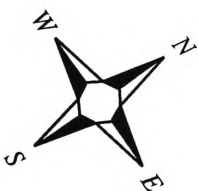
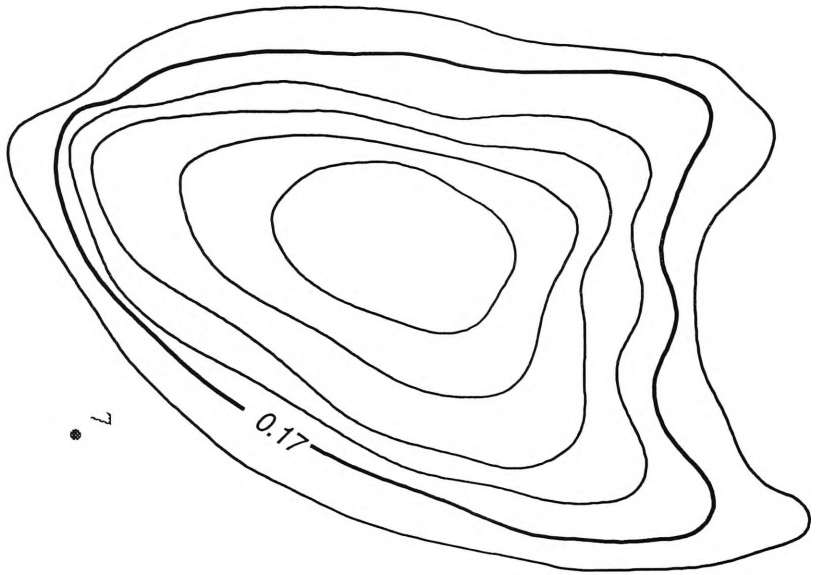
0 5 m

Contour Interval = 0.1m

•<sup>13</sup> Survey bench marks



Walvis Bay #3  
Survey 6  
8 October 1989



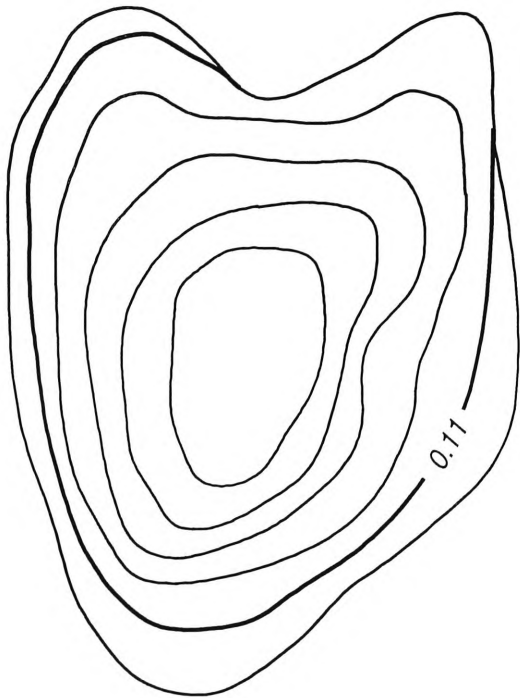
0 ————— 5 m

Contour Interval = 0.1m

• 13 Survey bench marks

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• 13  
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Walvis Bay #3  
Survey 7  
20 October 1989



0 5 m

Contour Interval = 0.1m

• 13 Survey bench marks

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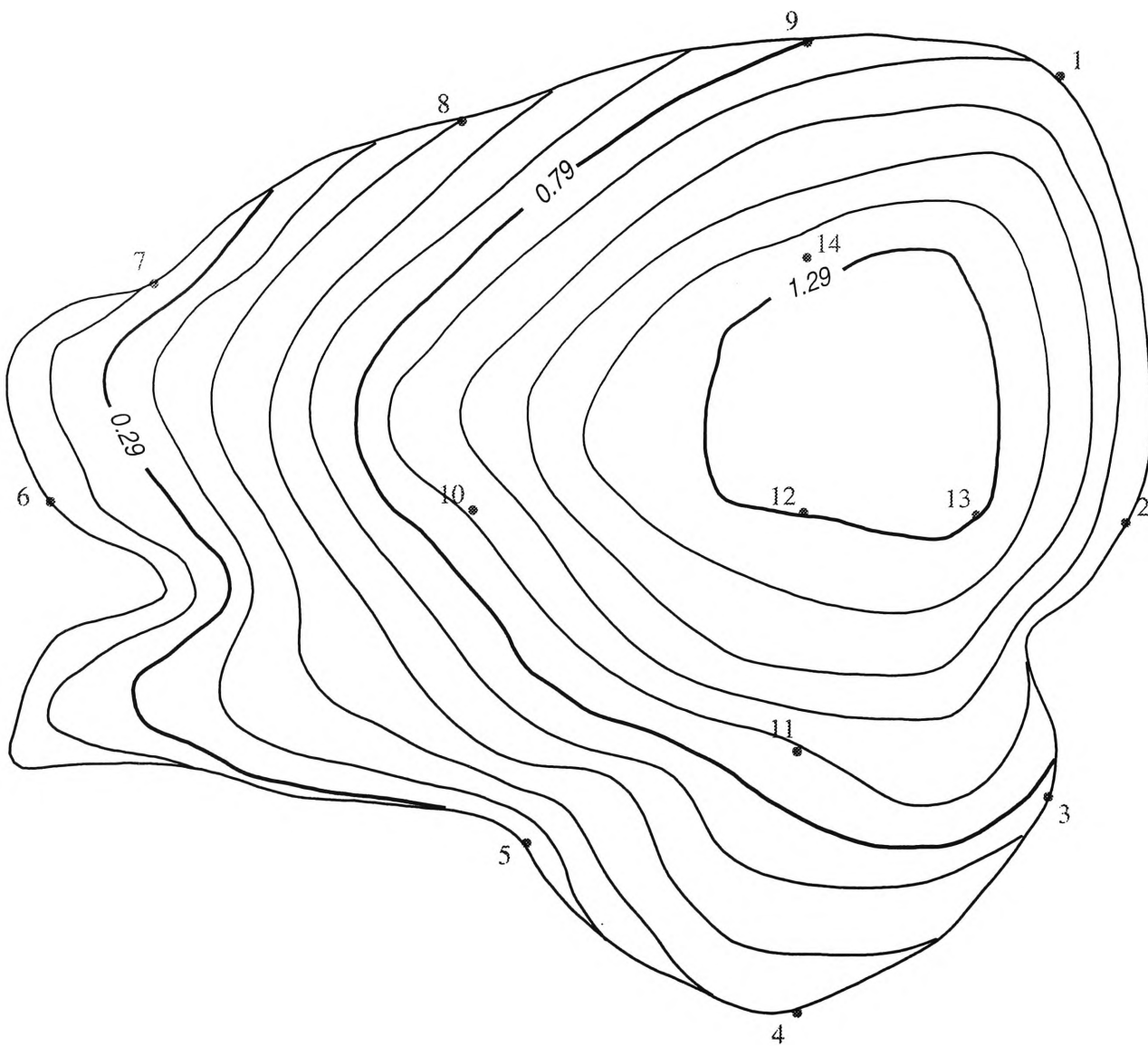
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Swakopmund #1  
Survey 1  
9 July 1989

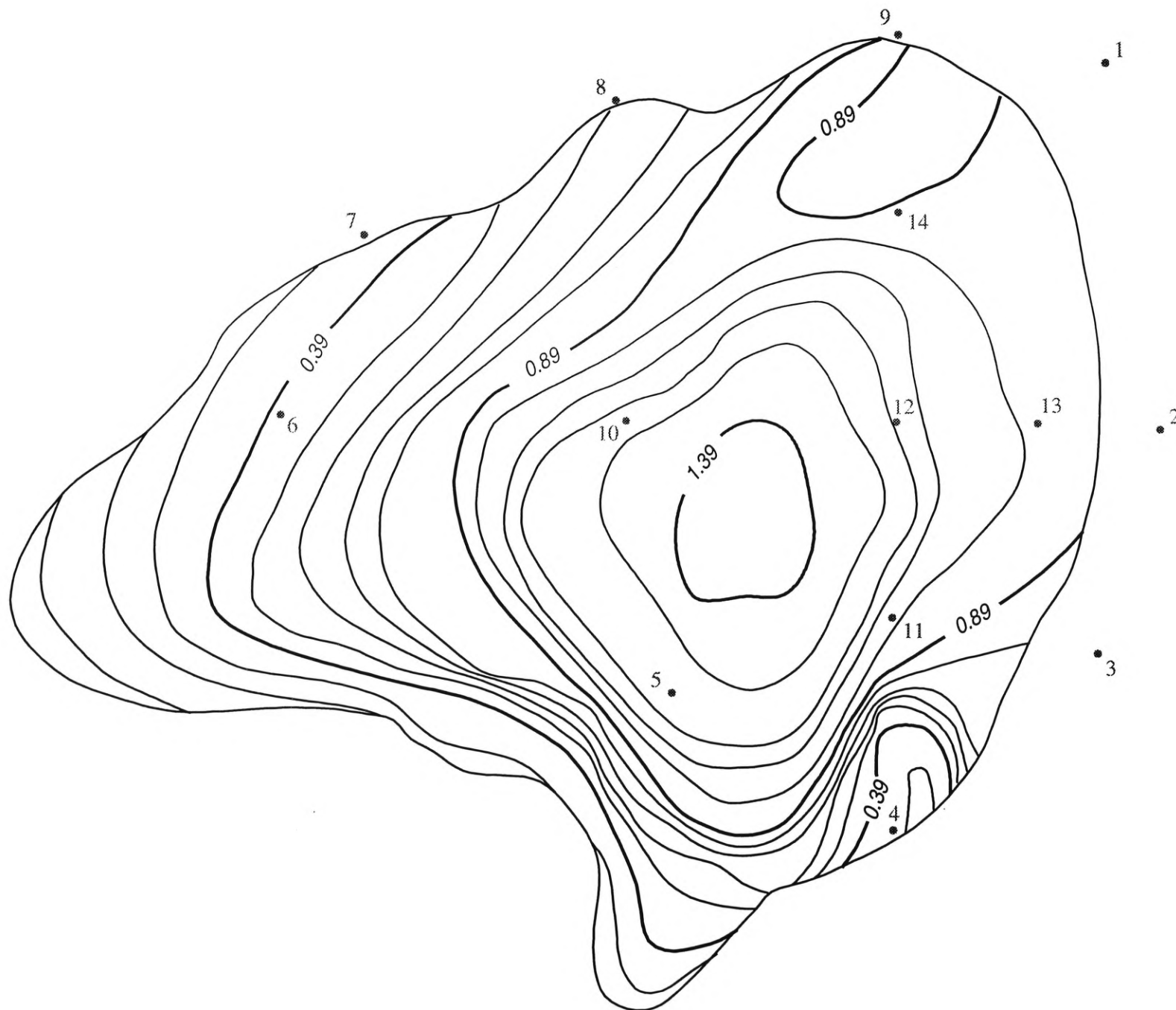


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Contour Interval = 0.1m

• 13 Survey bench marks

Swakopmund #1  
Survey 2  
30 July 1989



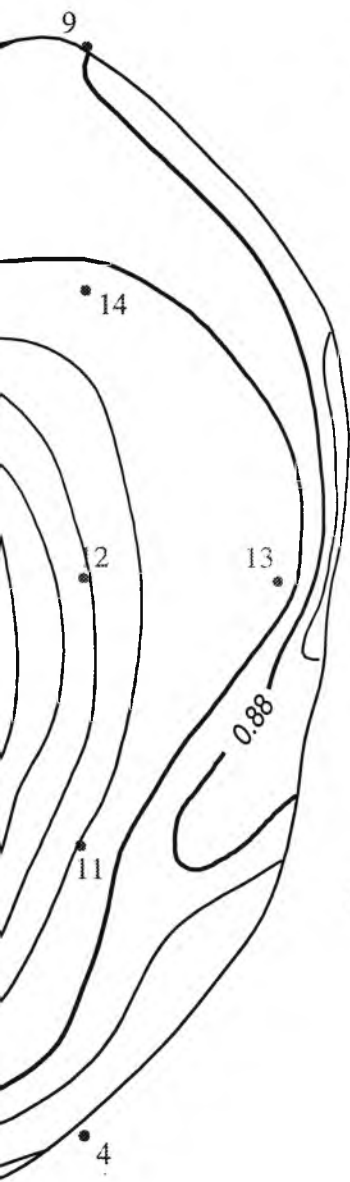
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• 13 Survey bench marks



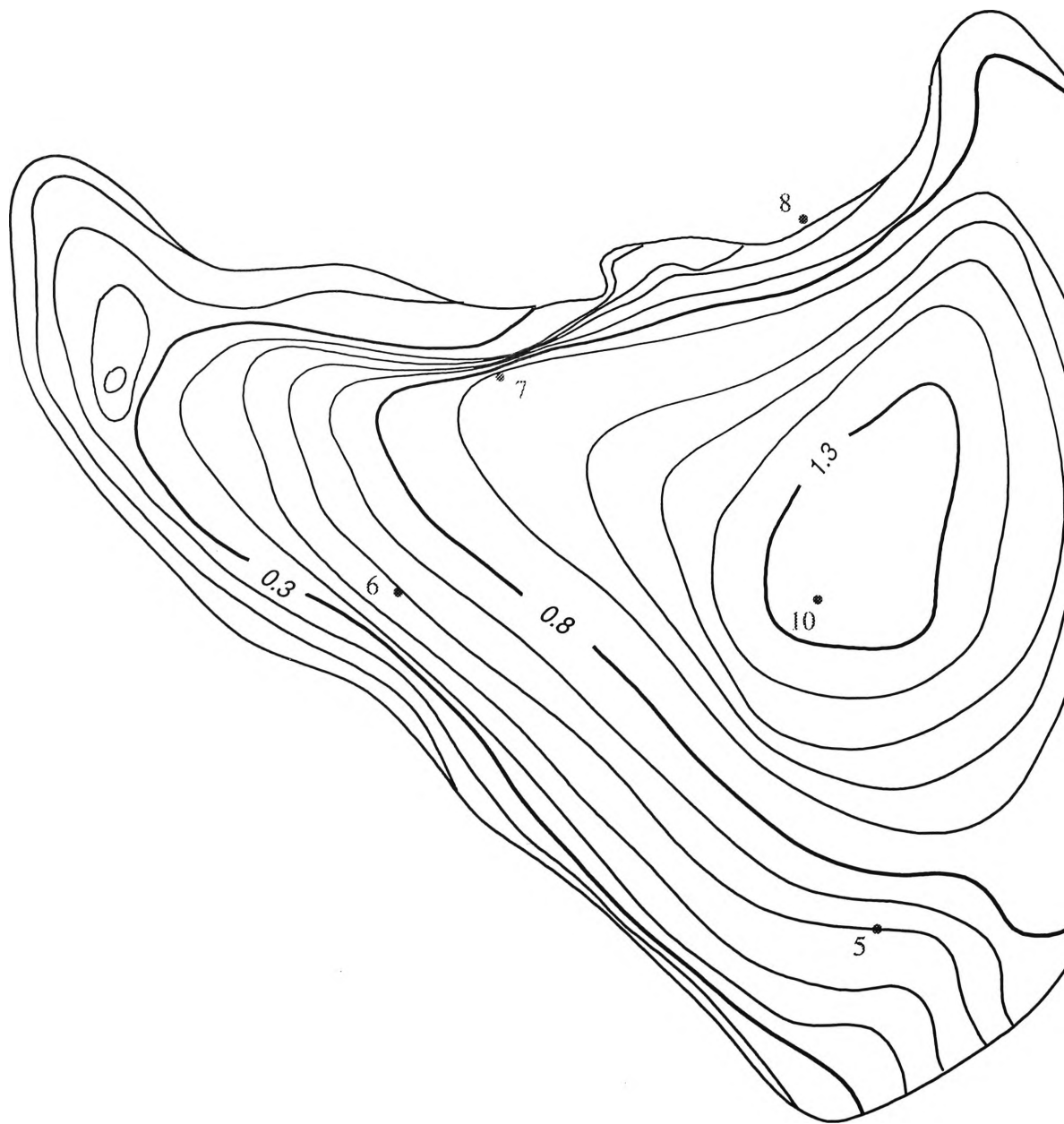
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Survey 3  
13 August 1989



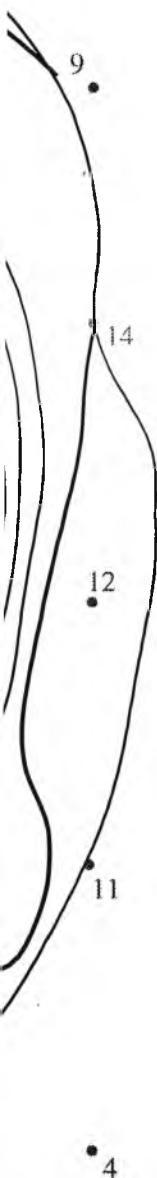
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• 13 Survey bench marks



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Survey 4  
30 August 1989

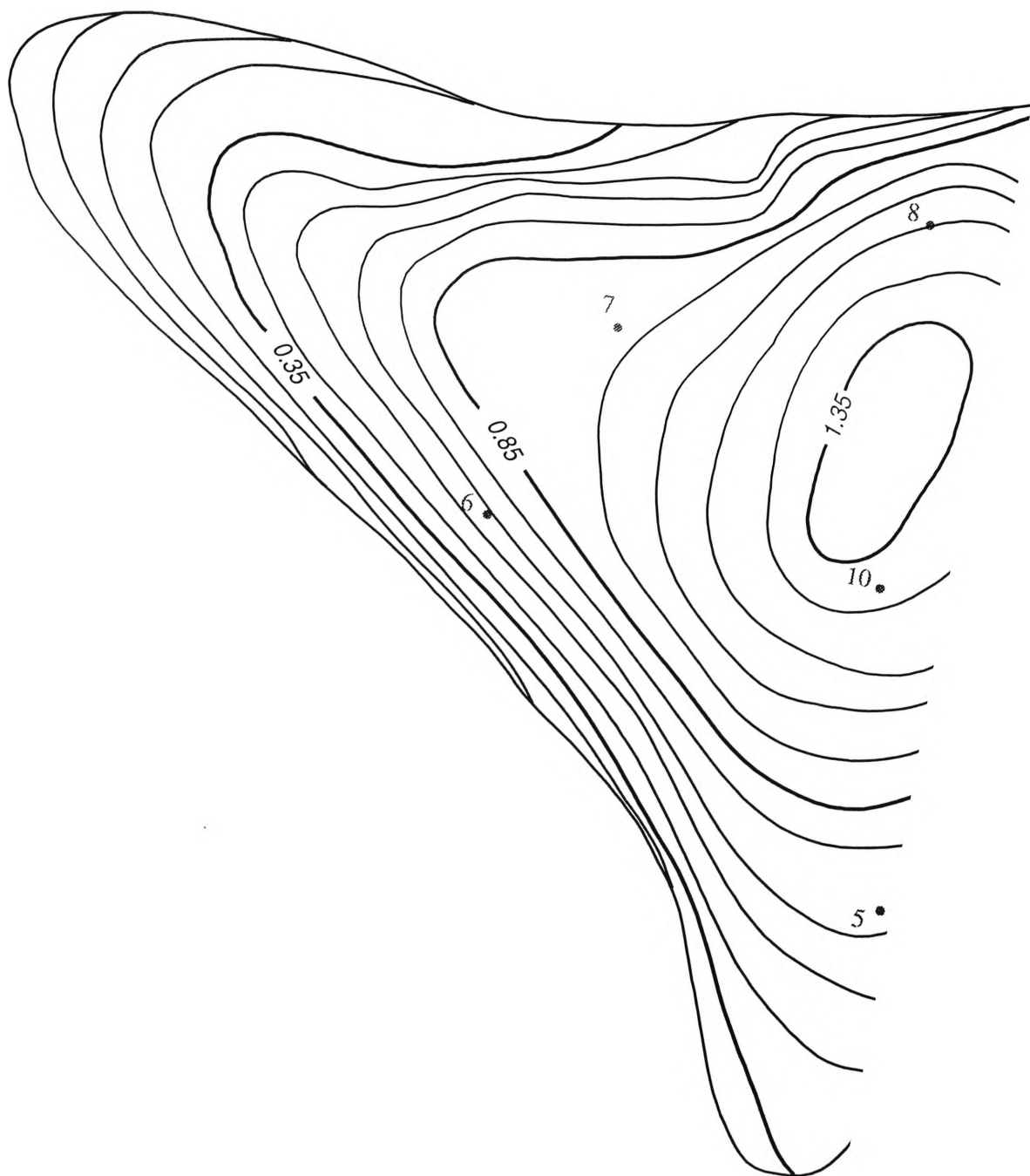


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• 13 Survey bench marks





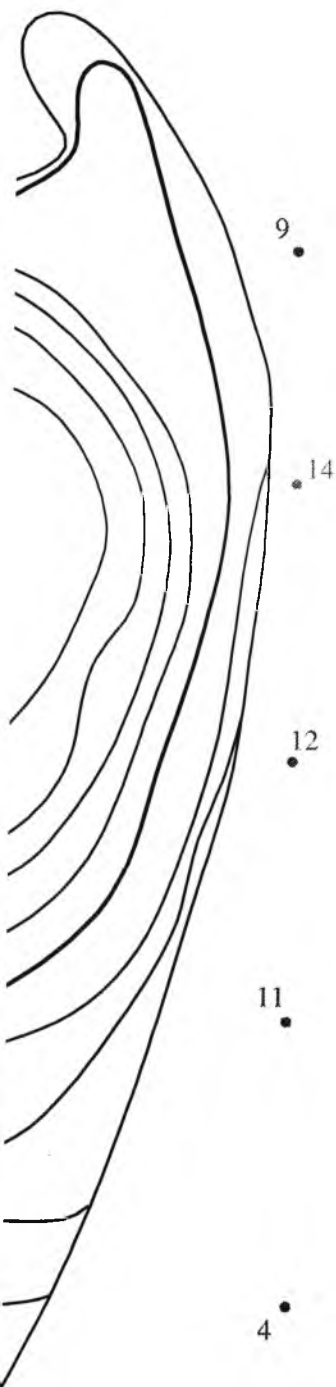
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Survey 5  
17 September 1989

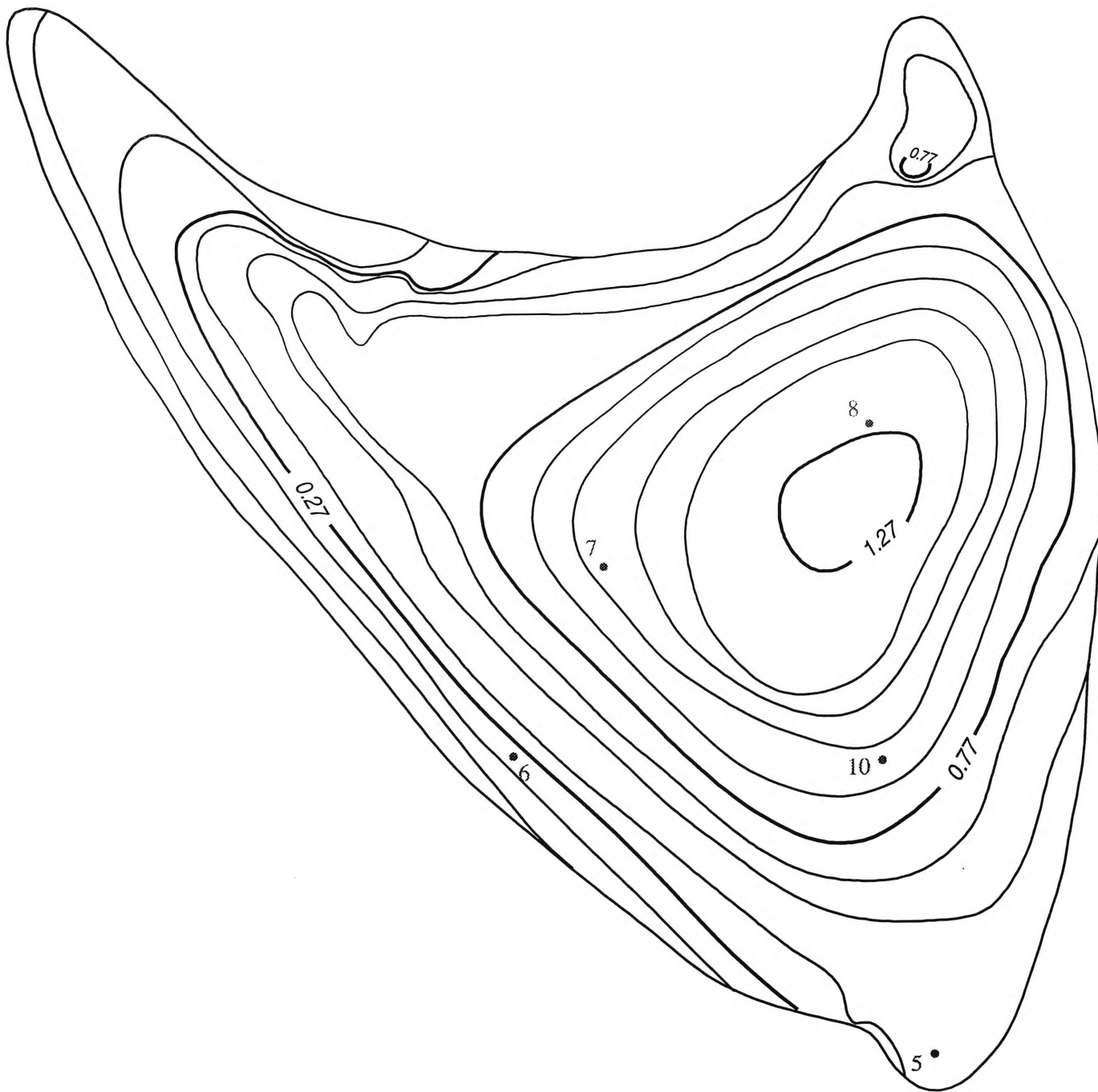


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Contour Interval = 0.1m

• 13 Survey bench marks





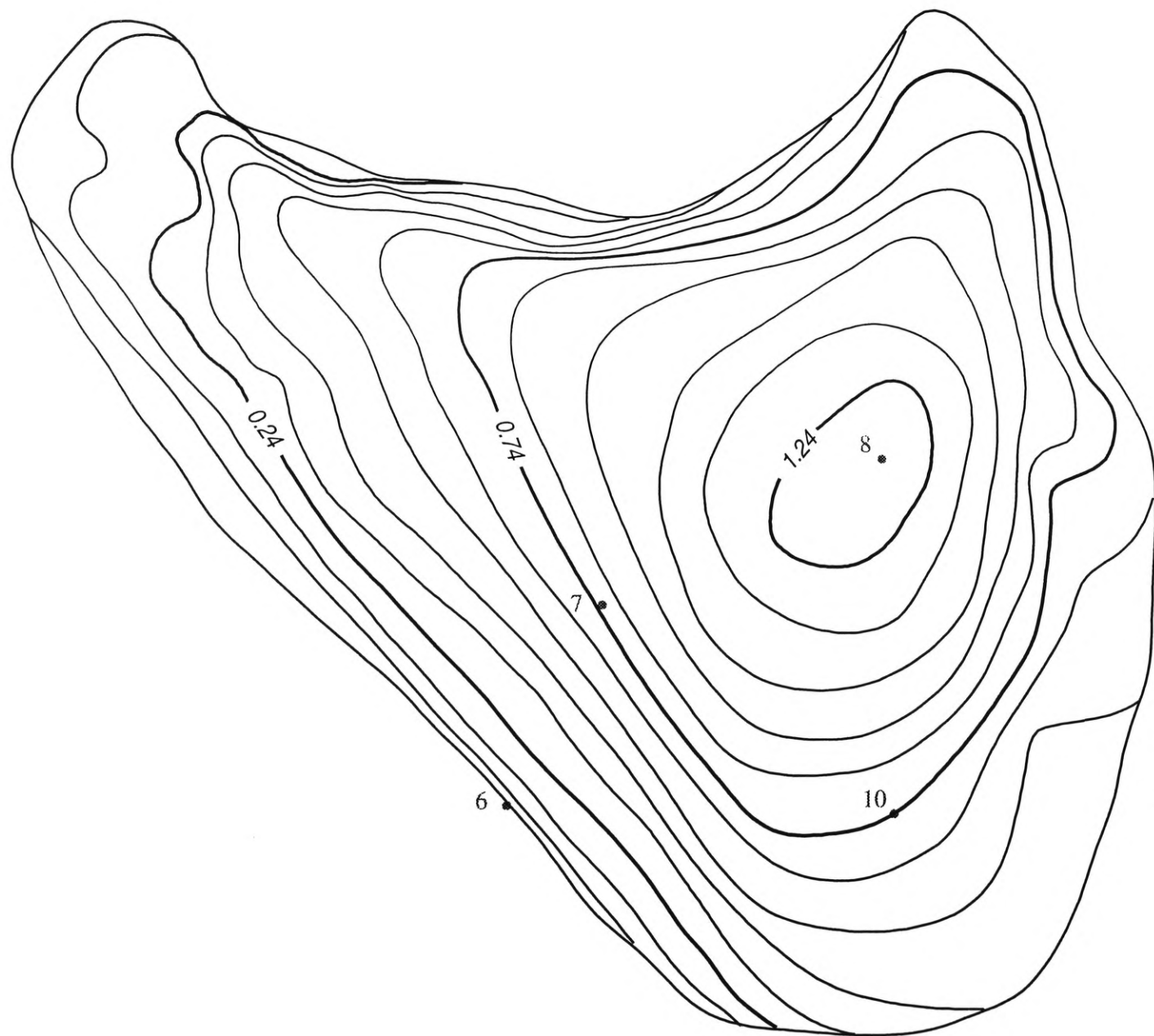
Swakopmund #1  
Survey 6  
7 October 1989



0 ————— 5 m

Contour Interval = 0.1m

• 13 Survey bench marks



Swakopmund #1  
Survey 7  
23 October 1989

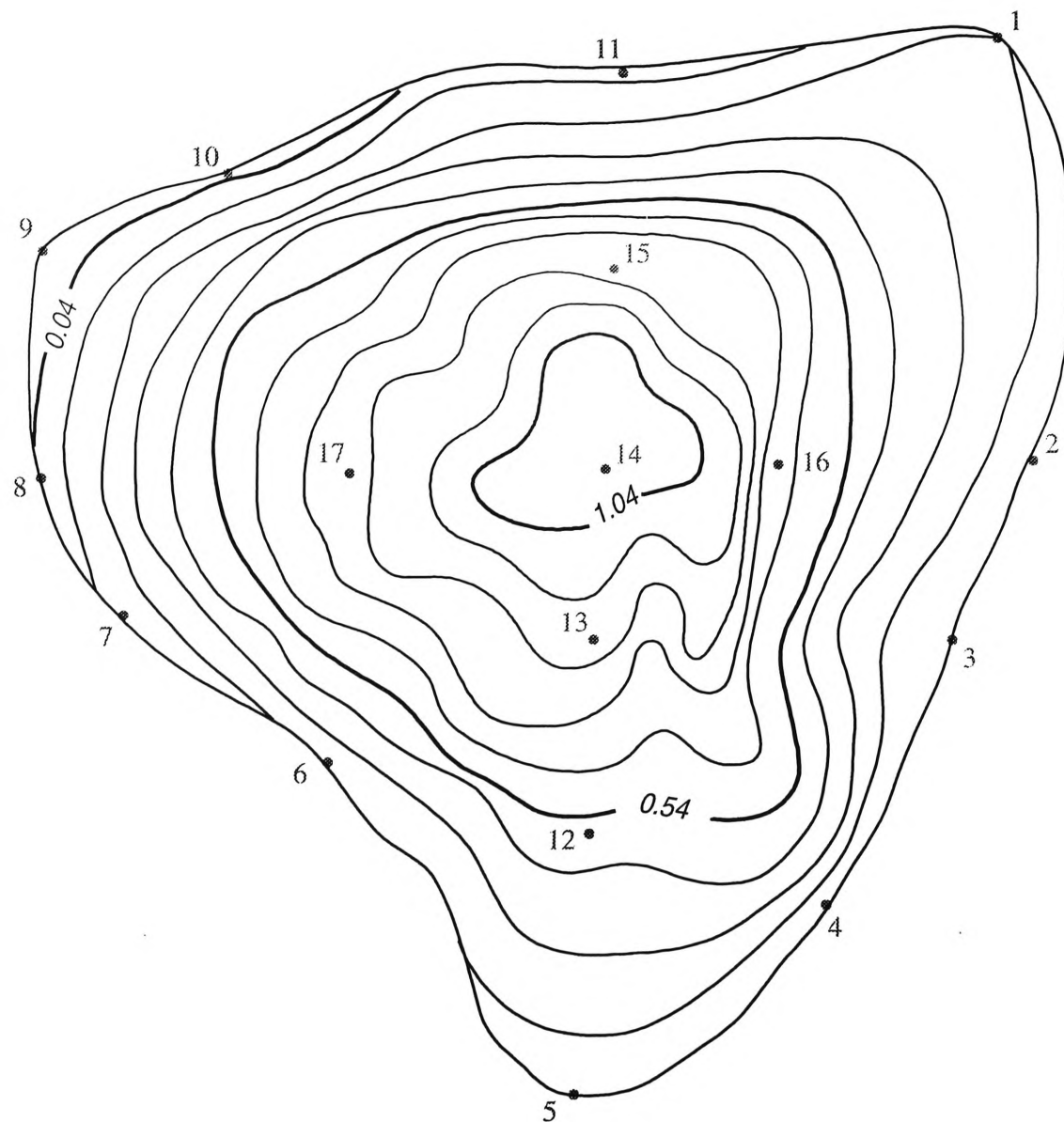


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Contour Interval = 0.1m

• 13 Survey bench marks

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Survey 1  
9 July 1989

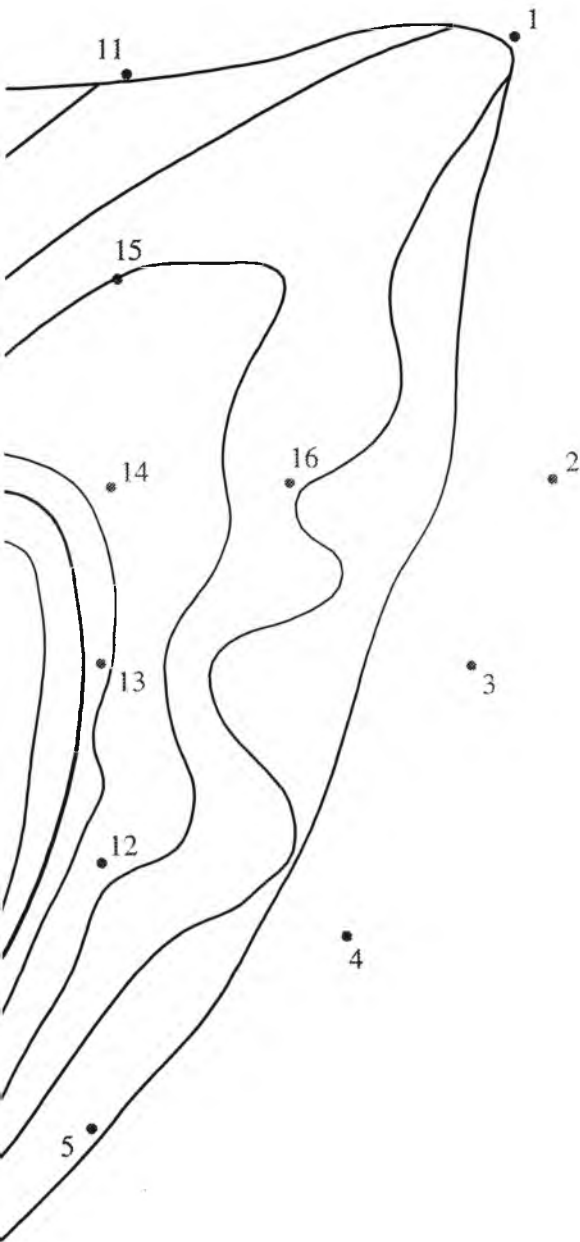


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Contour Interval = 0.1m

• 13 Survey bench marks





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Survey 2  
30 July 1989

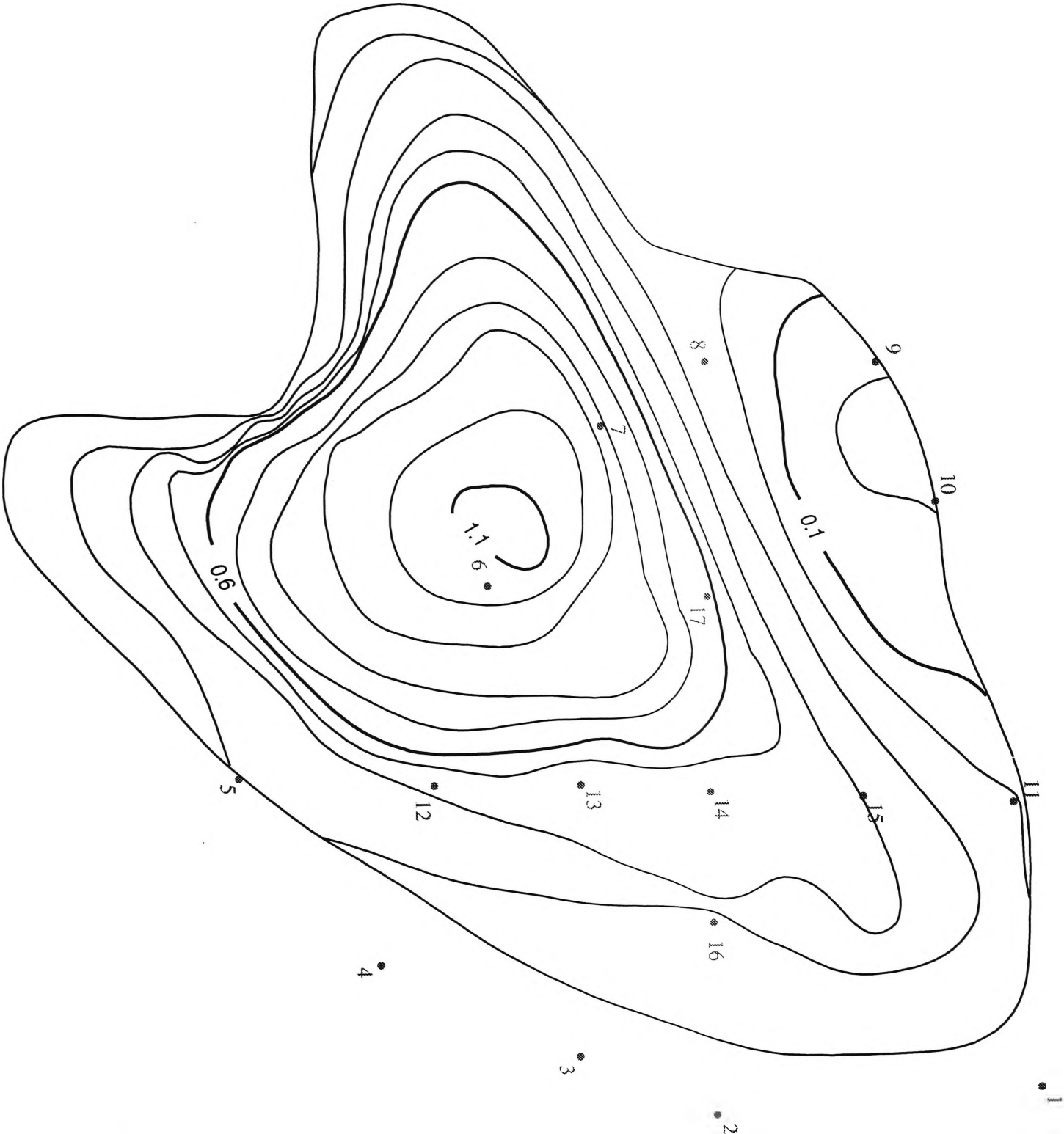


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Contour Interval = 0.1m

• 13 Survey bench marks

Swakopmund #2  
Survey 3  
13 August 1989

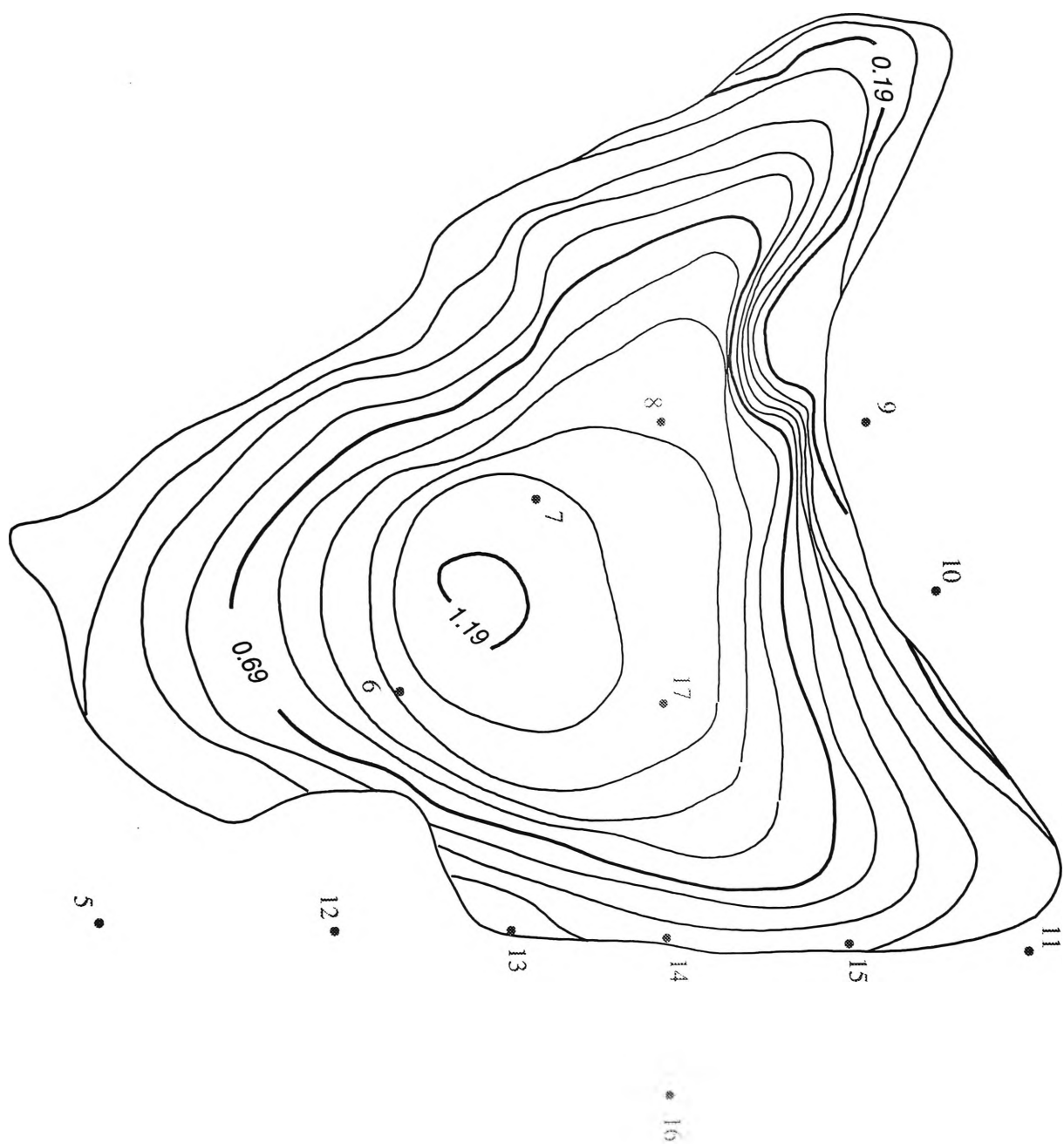


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• 13 Survey bench marks





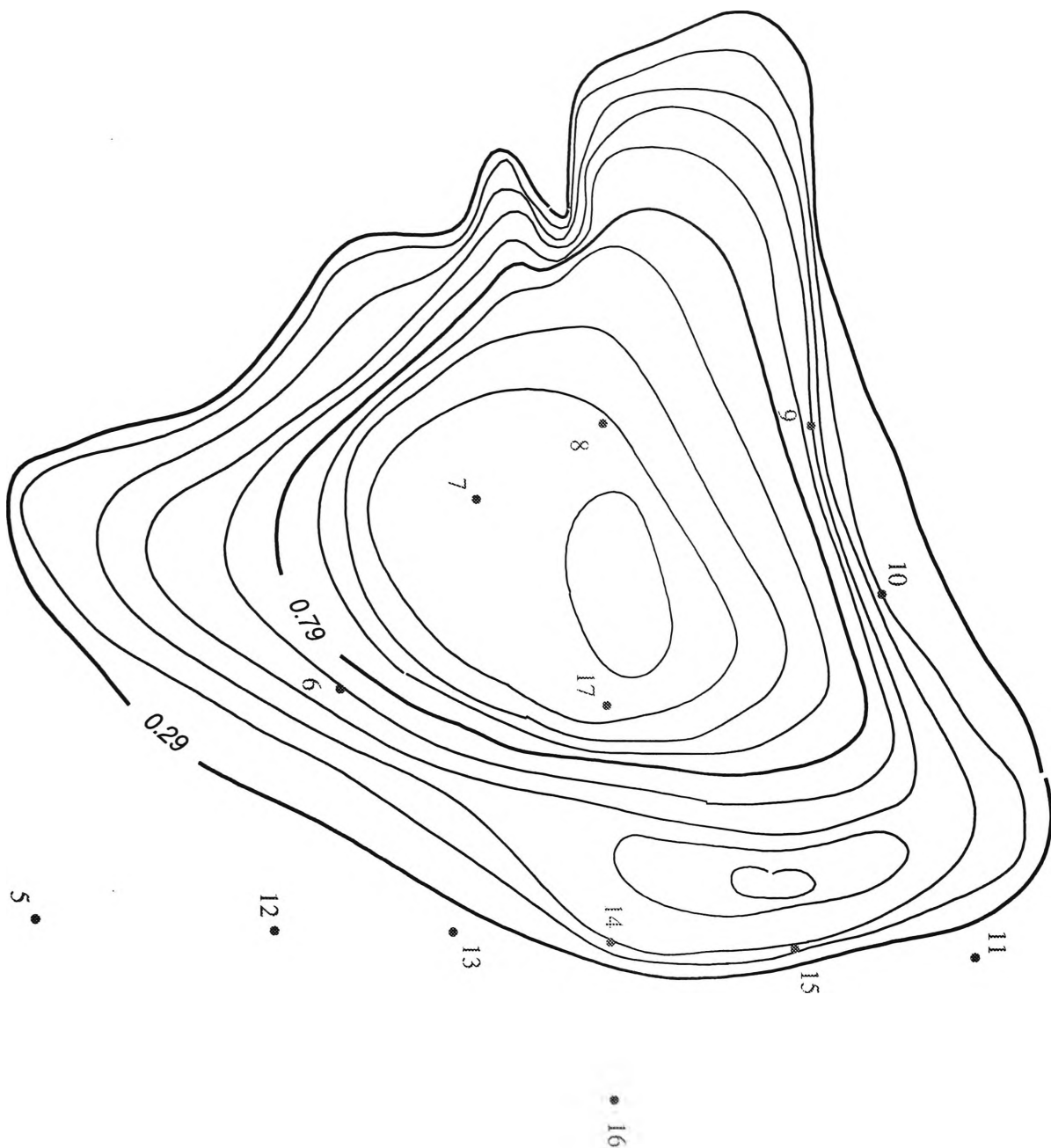
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Survey 4  
30 August 1989



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• 13 Survey bench marks



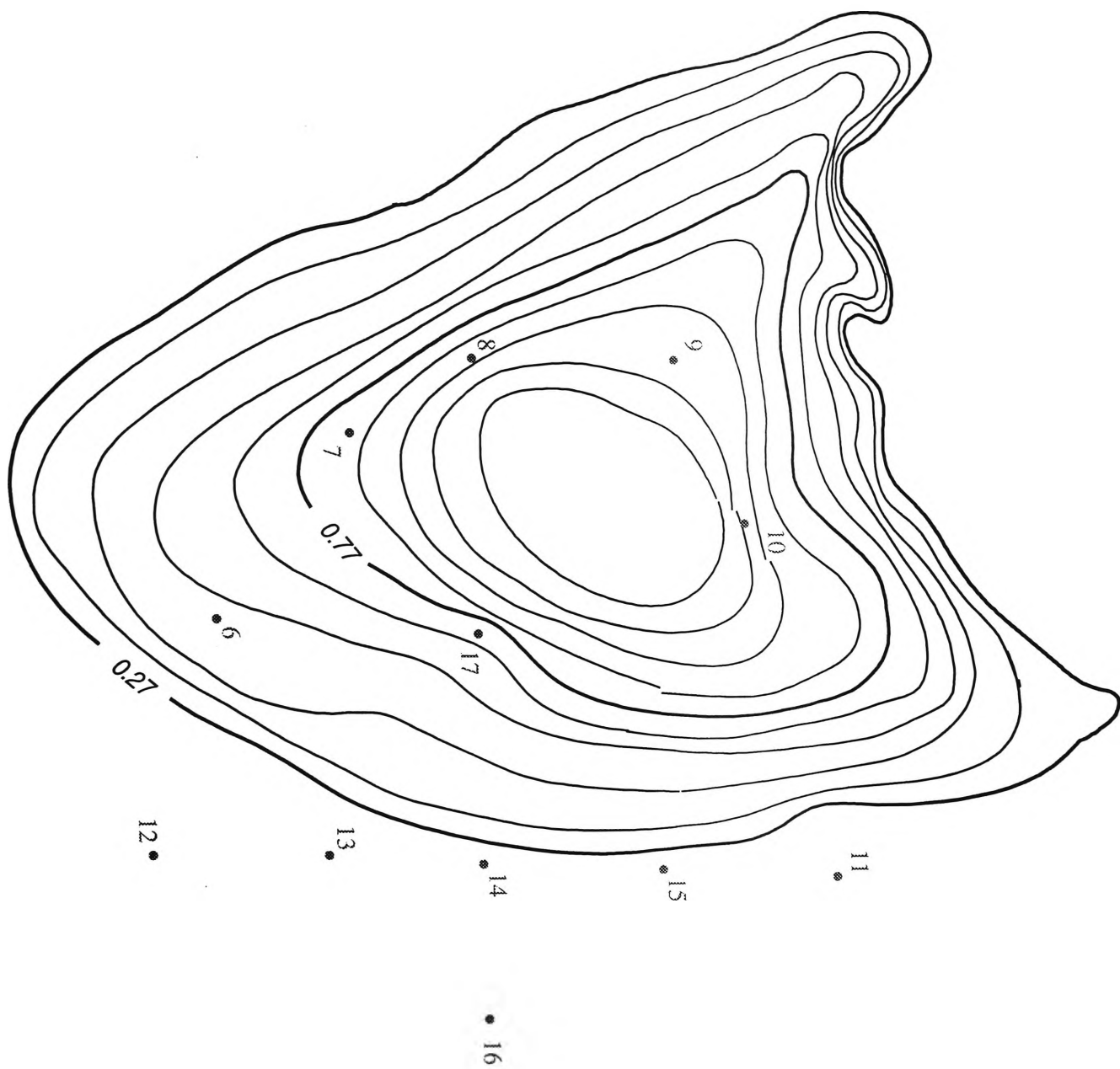
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Survey 5  
17 September 1989



0 5 m

Contour Interval = 0.1m

• 13 Survey bench marks



Swakopmund #2  
Survey 6  
7 October 1989



0 ————— 5 m

Contour Interval = 0.1m

• 13 Survey bench marks



Swakopmund #2  
Survey 7  
23 October 1989



0 ————— 5 m

Contour Interval = 0.1m

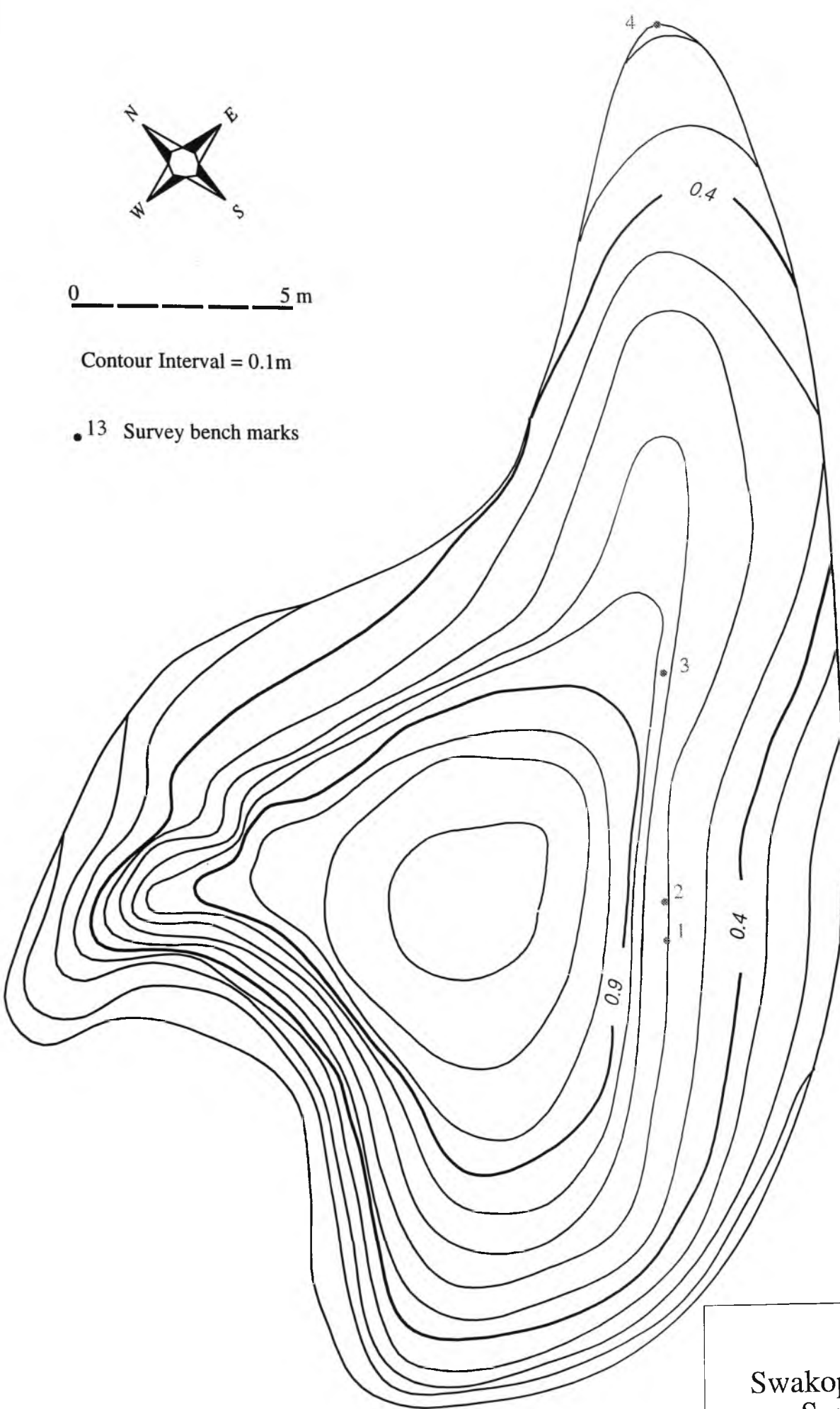
• 13 Survey bench marks



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Contour Interval = 0.1m

• 13 Survey bench marks



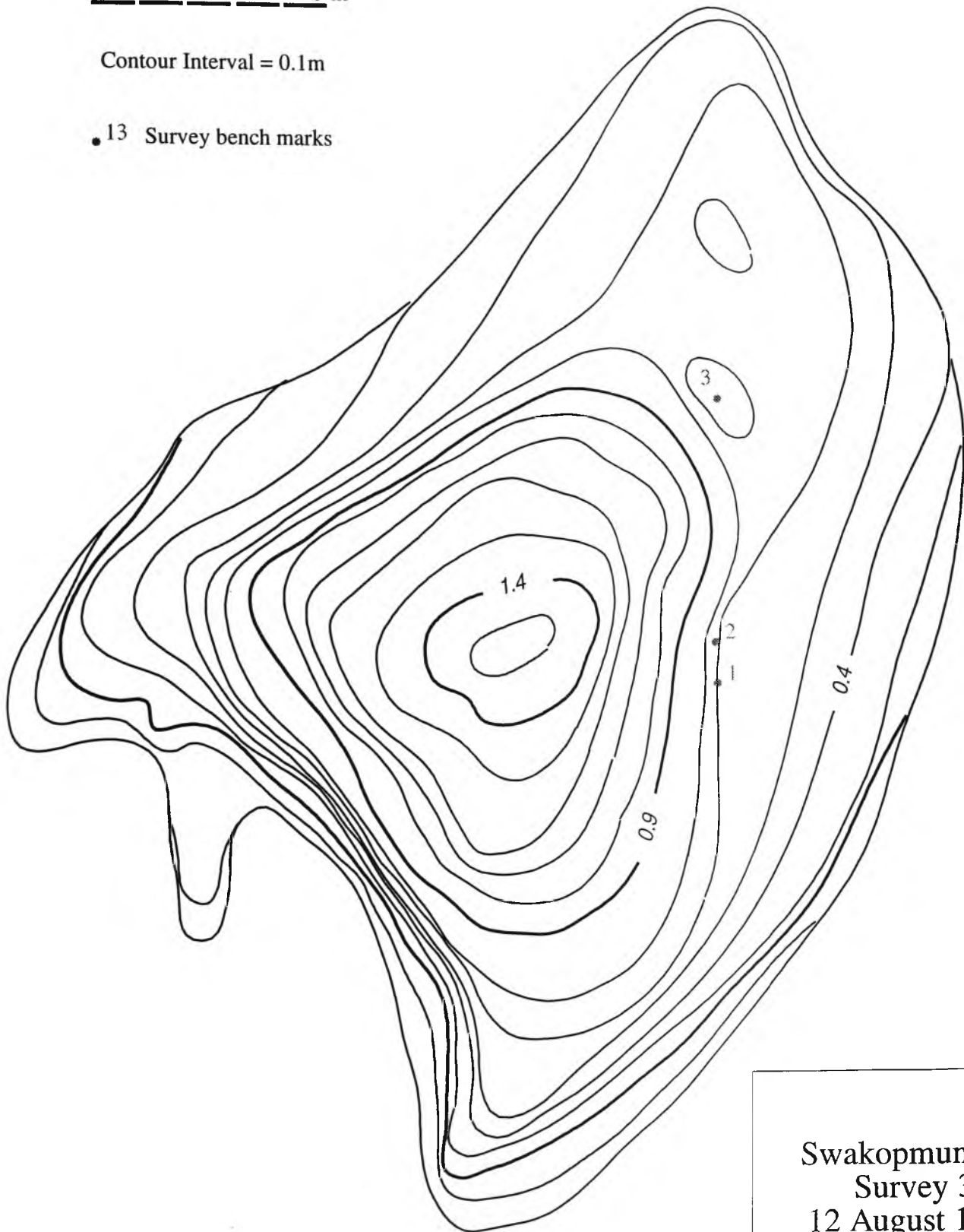
Swakopmund #3  
Survey 2  
30 July 1989



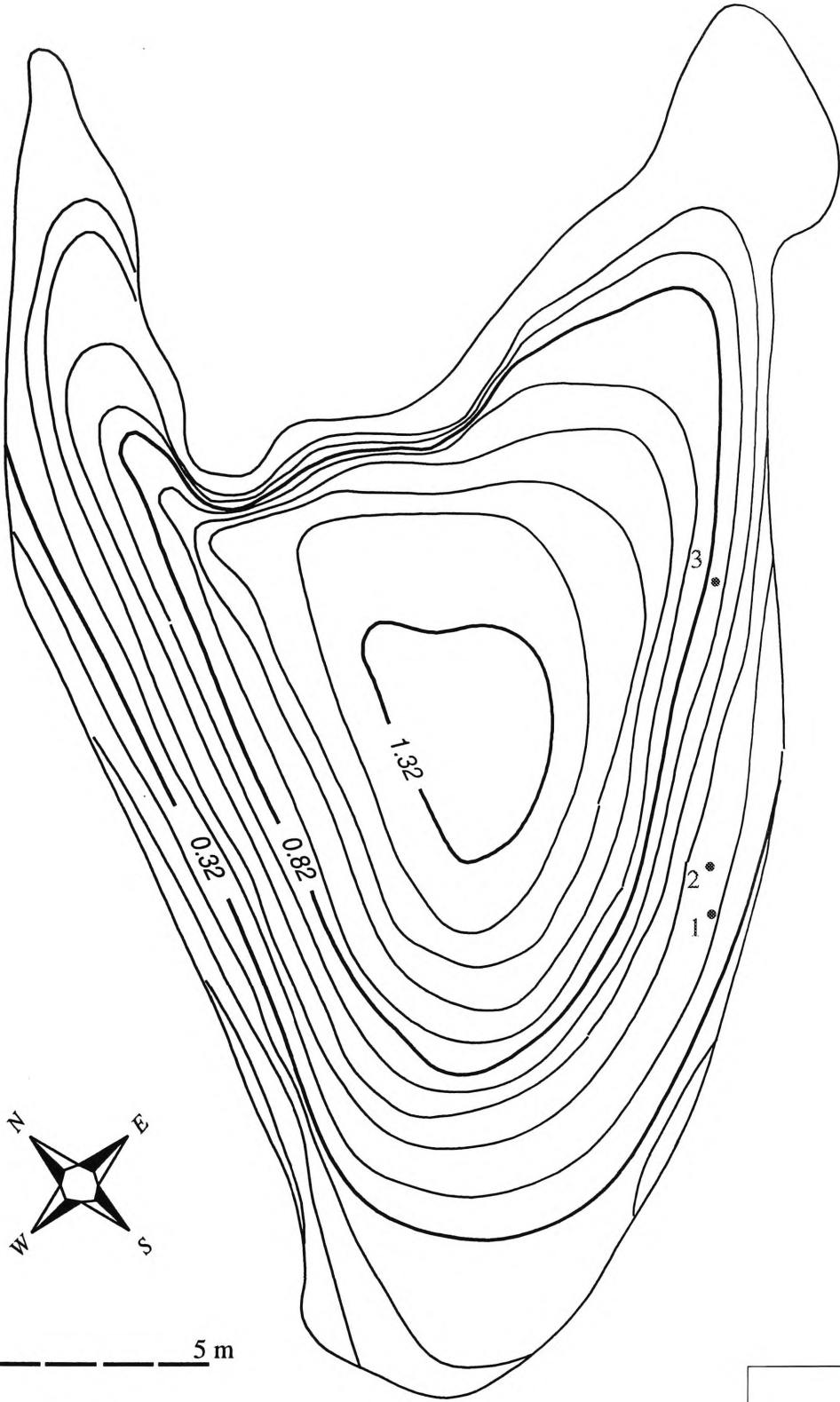
0 ————— 5 m

Contour Interval = 0.1m

• 13 Survey bench marks



Swakopmund #3  
Survey 3  
12 August 1989

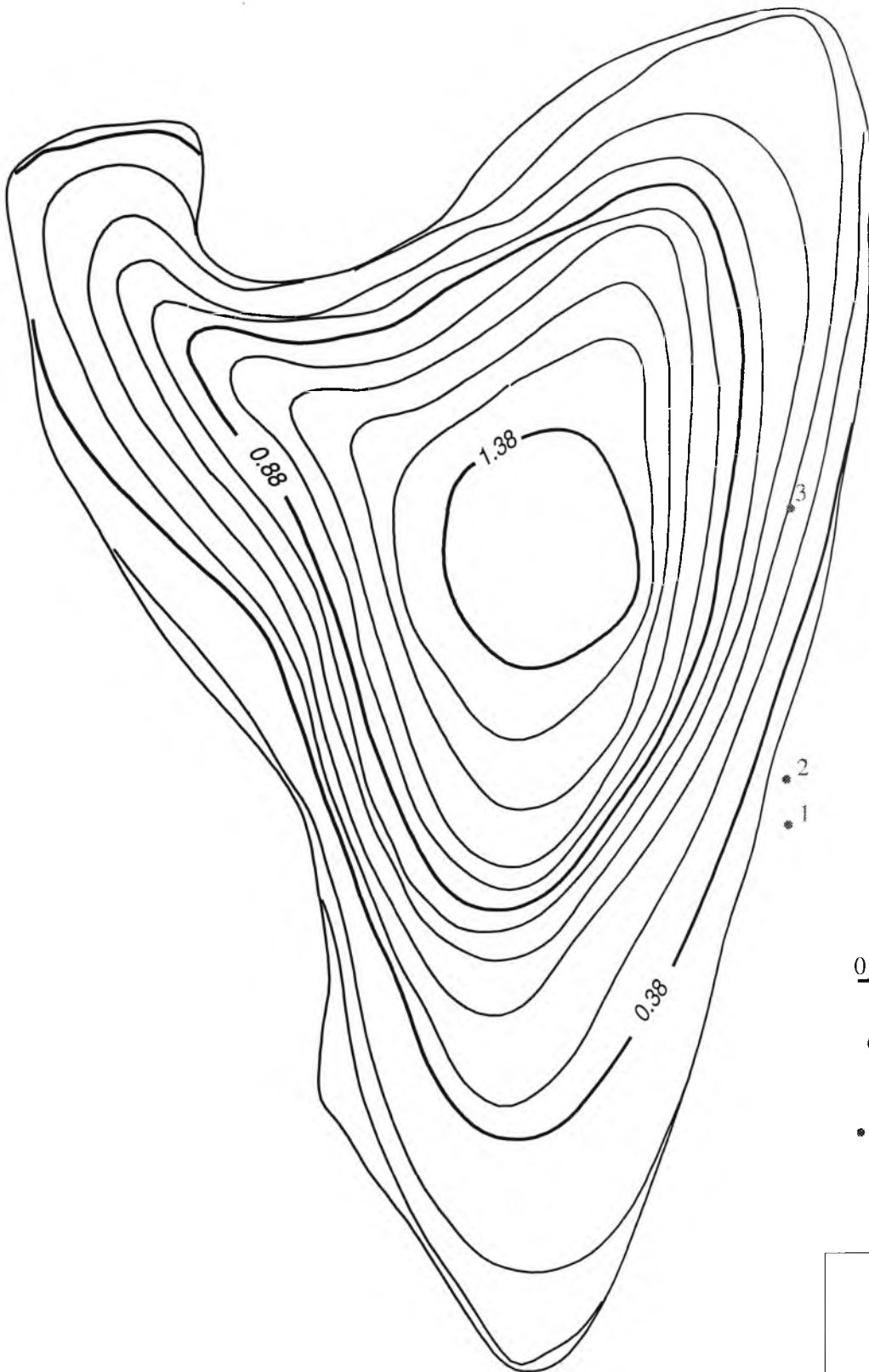


0 5 m

Contour Interval = 0.1m

• 13 Survey bench marks

Swakopmund #3  
Survey 4  
30 August 1989



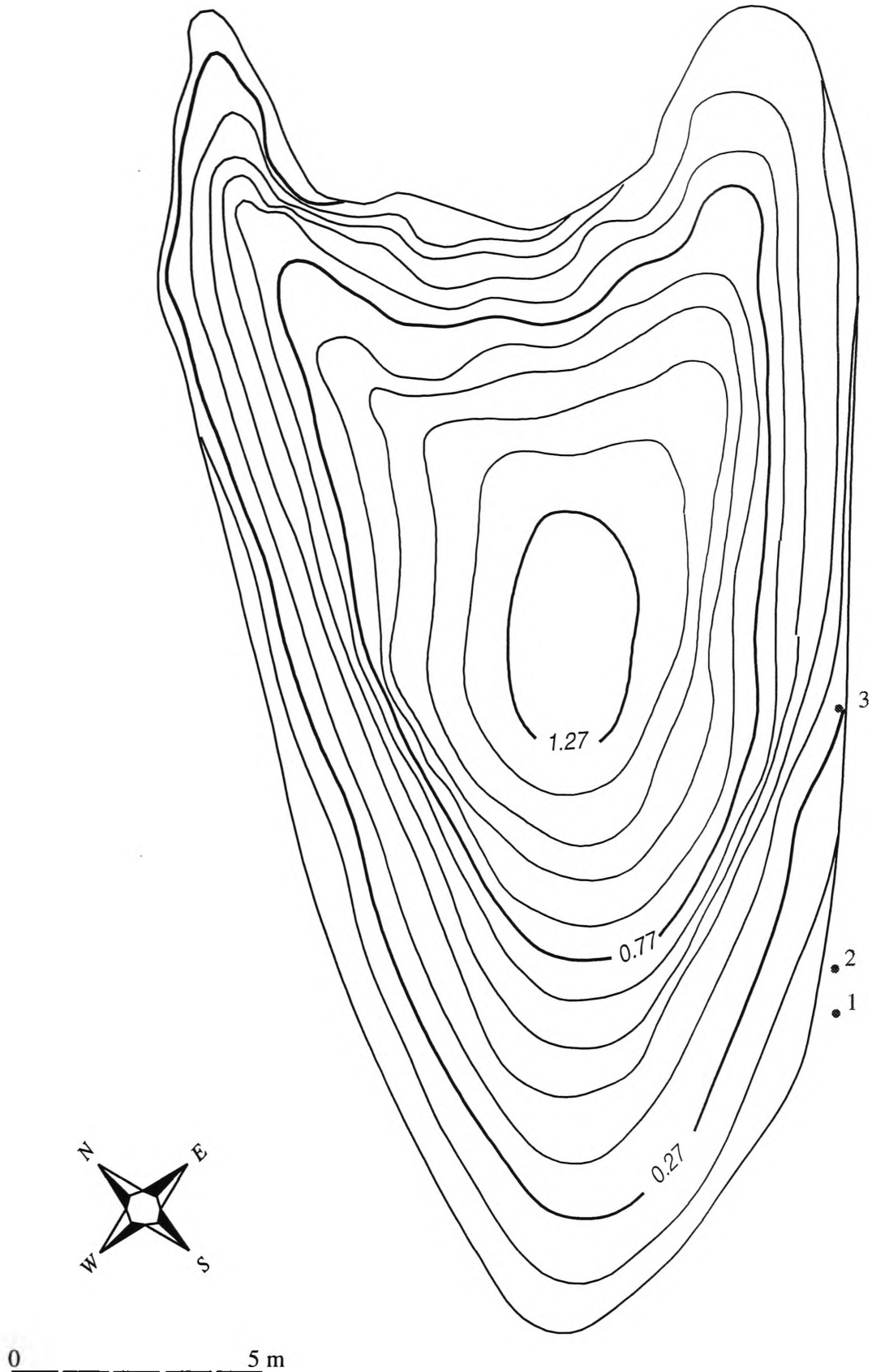
0 5 m

Contour Interval = 0.1m

• 13 Survey bench marks

Swakopmund #3  
Survey 5  
17 September 1989



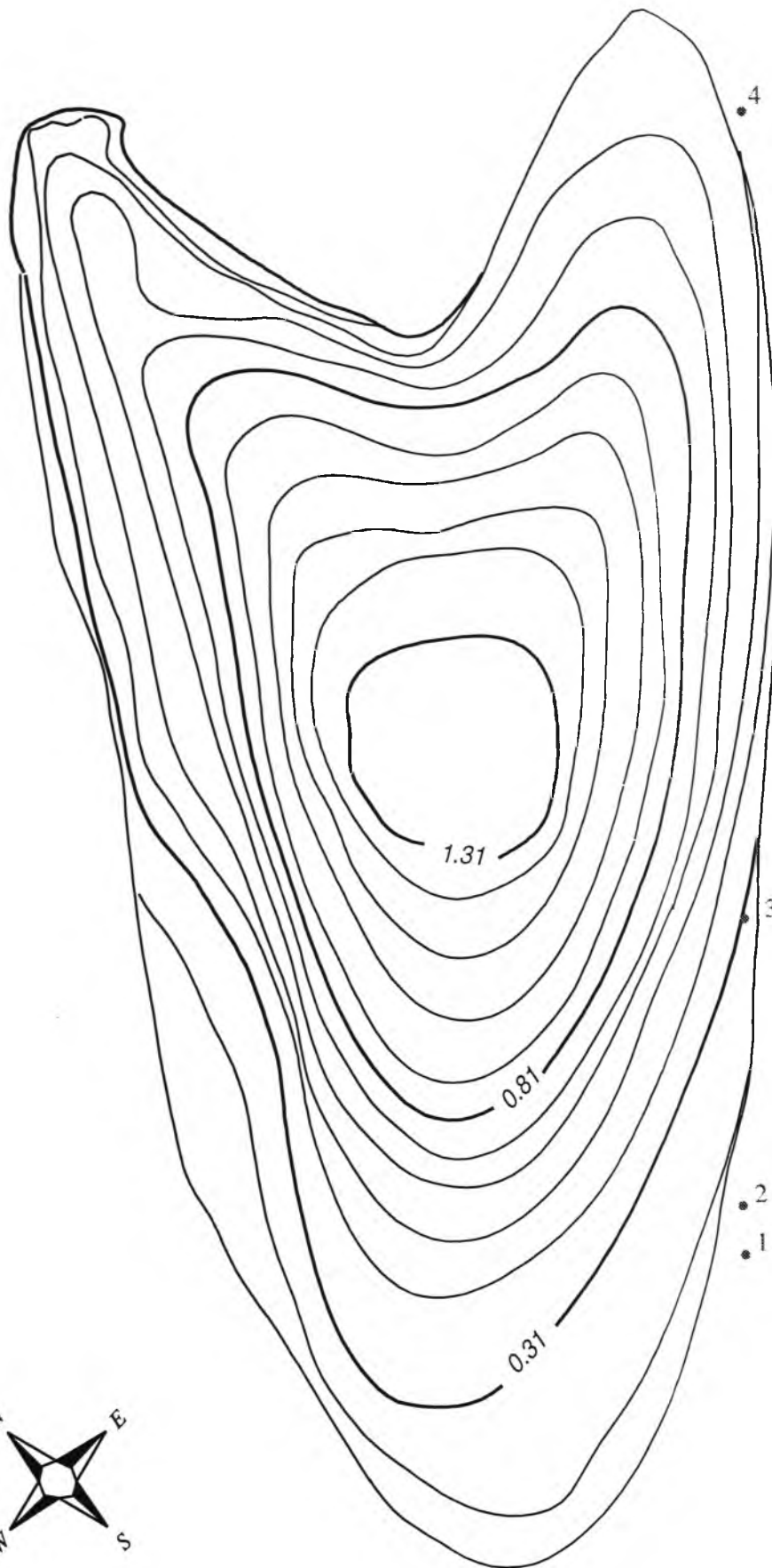


0 5 m

Contour Interval = 0.1 m

• 13 Survey bench marks

Swakopmund #3  
Survey 6  
7 October 1989



0 5 m

Contour Interval = 0.1m

• 13 Survey bench marks

Swakopmund #3  
Survey 7  
28 October 1989

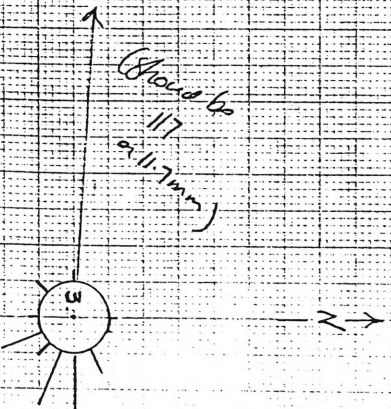
## **APPENDIX II**

### **Wind resultant equation**

(Vel cat)	mean wind velocity (V)	(V <sup>2</sup> )	(V-V <sub>t</sub> )	V <sup>2</sup> (V-V <sub>t</sub> )/100
4-6	5	25	1	0.3
7-10	8.5	72.3	4.5	3.3
11-16	13.5	182.3	9.5	17.3
17-20	18.5	342.3	14.5	49.6

$V_t = 4 \text{ m/sec}$

weighting factors (wf)



DP = 399.6 ✓  
 RDP = 117  
 RDP/DP = 0.28

9-27 JULY

	VECTOR UNITS				(DP - DP <sub>0</sub> )
	4-6	7-10	11-16	17-20	N
N	0.9   0.3	0.9   3.0	-	-	3.3 (1.1)
NNE	1.7   0.5	-	-	-	0.5 (0.7)
NE	-	-	-	-	-
ENE	1.7   0.5	3.0   9.9	-	-	10.4 (3.5)
E	2.0   0.6	19.6   64.7	11.9   205.9	0.9   44.6	35.8 (105.3)
ESE	9.4   2.8	6.8   22.4	-	-	25.2 (8.4)
SE	-	2.1   6.9	-	-	6.9 (2.3)
SSE	9.8   2.9	4.7   15.5	-	-	8.4 (6.1)
S	6.0   1.8	0.9   3.0	-	-	4.8 (1.6)
SSW	1.3   0.4	-	-	-	0.4 (0.14)
SW	3.8   1.1	1.7   5.6	-	-	6.7 (2.2)
WSW	0.4   0.1	-	-	-	0.1 (0.04)
W	2.1   0.6	1.3   4.3	-	-	4.9 (1.6)
WNW	0.9   0.3	-	-	-	0.3 (0.1)
NW	6.0   1.8	-	-	-	1.8 (0.6)
NNW	0.4   0.1	-	-	-	0.1 (0.04)
	46.5	41	11.9	0.9	

no. of obs / total obs

vector units

TOTAL obs = 235

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 FRYBERGER  
 RESULTS

		cos	DP	cos x DP	sin	sin x DP
0°	N	1	3.3	3.3	0	0
22.5°	NNE	0.92	0.5	0.46	0.38	0.19
45°	NE	0.71	—	0.71	0.71	0.71
57.5°	ENE	0.38	10.4	3.95	0.92	9.57
90°	E	0	315.8	0	1	315.8
125°	ESE	-0.38	25.2	-9.58	0.92	23.2
135°	SE	-0.71	6.9	-4.9	0.71	4.9
157.5°	SSE	-0.92	18.4	-16.9	0.38	6.99
180°	S	-1	4.8	-4.8	0	0
202.5°	SSW	-0.92	0.4	-0.37	-0.38	-0.15
225°	SW	-0.71	6.7	-4.76	-0.71	-4.76
247.5°	WSW	-0.38	0.1	-0.04	-0.92	-0.09
270°	W	0	4.9	0	-1	-4.9
292.5°	WNW	0.38	0.3	0.11	-0.92	-0.28
315°	NW	0.71	1.8	1.28	-0.71	-1.28
337.5°	NNW	0.92	0.1	0.09	-0.38	-0.04
				-31.45	349.86	

$$RDP = \sqrt{x^2 + y^2}$$

$$x = -31.45$$

$$x^2 = 989.1$$

$$y = 349.86$$

$$y^2 = 122,402$$

$$= 989.1 + 122,402$$

$$= \sqrt{123,391}$$

$$= 351$$

$$RDP = 351 \text{ (Magnitude [or length of arrow] of RDP)}$$

$$= 351/3 = 117$$

$$RDP = \tan^{-1} \frac{y}{x}$$

$$= \frac{349.86}{-31.45} \tan^{-1}$$

$$= -84.86$$

(plot backwards) →

Note: Since the DP values were plotted as DP/s, then the RDP value was also plotted as RDP/s.

SURVEY 1-2